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Steam Stripping of Fixed-Bed Gasification Wastewaters

Radian Corp., Austin, TX

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STEAM STRIPPING OF FIXED-BED GASIFICATION WASTEWATERS

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ABSTRACT

Laboratory- and bench-scale steam stripping tests were conducted using gas liquor from a fixed-bed coal gasifier at the Department of Energy's Morgantown Energy Technology Center (DOE-METC). The gas liquor was pretreated by solvent extraction for phenol removal and filtered prior to stripping. This report presents the results of the wastewater stripping tests and provides engineering and environmental data for the design of steam strippers for fixed-bed gasification wastewaters. The laboratory tests were performed primarily to determine the effect of pH on contaminant removals. During the bench-scale tests, samples of influent, effluent, and overhead vapor and condensate were analyzed for a number of species of potential environmental concern (dissolved gases, sulfur and nitrogen species, trace metals, organics, and other water quality parameters). Mass transfer coefficients for ammonia, carbon dioxide, and hydrogen sulfide stripping were calculated.

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SECTION 1

INTRODUCTION

1.1 BACKGROUND

The raw gas liquor resulting from fixed-bed coal gasification processes contains a number of contaminants, some of which are present in relatively high concentrations. These include tars and oils, dissolved organics (especially phenols), dissolved gases (e.g., NH_3, HCN, H_2S, CO_2), and both suspended and dissolved inorganics. Removal of these contaminants in a multiple step wastewater treatment system has been included in many proposed commercial coal gasification plant designs.

Steam stripping for the removal (and in some cases, recovery) of dissolved ammonia and acid gases is a treatment process which is common to most of these designs. Capital and operating costs for steam stripping systems can account for a significant portion of the overall cost of wastewater treatment in coal gasification plants. There is a need, therefore, to develop design data that can be used to maximize the cost effectiveness of this process. In addition, the outlet streams need to be characterized to evaluate the effects of contaminants on downstream process performance.

It should be noted that the terms "gas liquor" and "wastewater" are used synonymously throughout this report. It is recognized that steam stripping is but one of several treatment steps that would likely be required prior to discharge.

1.2 OBJECTIVES

The objectives of this project were:

- To provide data characterizing the various stripper outlet streams for species of environmental interest with respect to potential impacts on downstream process performance and environmental effects.

- To develop mass transfer data that could be used in the design of steam strippers for wastewater from the fixed-bed gasifiers following pretreatment by solvent extraction, filtration, and pH adjustment (if needed).

To meet these objectives, two series of tests were performed. First, laboratory-scale screening tests were conducted to determine the effect of wastewater pH on the removal of ammonia, H_2S, CO_2, HCN, and phenol. The results of these tests were used to determine the influent pH for a series of bench-scale runs in which samples of inlet and outlet streams were analyzed for species of potential environmental concern and which enabled mass transfer coefficients to be calculated.

1.3 REPORT CONTENTS

This report is organized as follows:

- Section 2 summarizes the results and conclusions of the laboratory- and bench-scale tests conducted during this project and presents additional technical needs.

- Section 3 describes the experimental approach followed to obtain bulk raw gas liquor samples and the procedures followed during the experimental runs.

- Section 4 presents the results of both series of experimental runs and the correlations developed from the data and discusses limitations and extrapolation of these results.

- Section 5 presents the results of the procedures followed to validate the experimental data from both test series.

- Section 6 gives a list of the references cited in the report.

- Appendices are included that give the detailed test data for the laboratory- and bench-scale tests, wastewater

handling and analysis methods including quality assurance/control techniques followed, and a discussion of the design operations/procedures for a packed bed stripping column.

SECTION 2

SUMMARY OF RESULTS, CONCLUSIONS, AND TECHNICAL QUESTIONS

Results, conclusions, and recommendations based on the data obtained from the two series of stripping tests performed using raw gas liquor from the METC gasifier wastewater are summarized below. Details are presented in subsequent sections of this report.

2.1 LABORATORY-SCALE TESTS

- Greater than 90% removals of dissolved ammonia and alkalinity (due to dissolved CO_2) were obtained by stripping this wastewater at the a pH of 8.6 (existing pH after solvent extraction) and higher. Ammonia removal increased from about 92% to over 99.9% as the initial wastewater pH was raised from 8.6 to 11.0. A decrease in CO_2 removal efficiency from over 99% to 96% was observed with increasing pH from 8.6 to 11.0.

- Dissolved H_2S removals decreased from 80% to 50% as the initial pH was increased from 8.6 to 11.0. Cyanide removals were between 10-20%; most of the cyanide content of this wastewater was present as fixed (and therefore non-strippable) cyanide at the pHs evaluated. It is likely that some of the free cyanide initially in the wastewater had been converted to fixed cyanide and/or thiocyanate and the removal may be higher for "fresh" wastewater.

- Removal of the small amount of phenol (total) remaining in the wastewater after pretreatment by solvent extraction was found to be less than 20%. No clear trends were observed as the pH was increased. Technical questions remain regarding phenol stripping for unextracted wastewater or wastewater having phenol levels closer to those expected from commercial gasifier systems.

- Because of its buffering capacity (due to HCO_3/CO_3 alkalinity), the wastewater required a significant quantity of lime to raise its pH from 8.6 to 11.0. In order to go

from the pH 8.6 to 9.5 required 470 milliequivalents (meq) of lime per liter; to go from pH 8.6 to pH 11.0 required nearly 1200 meq/L. The buffering capacity of the wastewater is readily reduced by steam stripping of the dissolved CO_2.

- Two-stage stripping would likely be required to remove all (or nearly all) of the dissolved ammonia and acid gas species (especially H_2S and HCN) from this wastewater.

- Stripping the wastewater at a pH of 8.6 produced significant quantities of solids that collected on the surfaces of the equipment and led to plugging problems. Increasing the pH to 9.5 or higher by lime addition significantly reduced the plugging problems. The solids are likely ammonium salts, possibly ammonium carbonate or ammonium carbamate. However, the solids were not analyzed.

2.2 BENCH-SCALE TESTS: ENVIRONMENTAL

- Thiocyanate, sulfate, fluoride, and chloride are not removed by steam stripping. These contaminants will be found in the stripper effluent stream.

- Trace elements detected in stripper outlet streams appear to be largely system contaminants, possibly from the column, ceramic packing, and the lime added for pH adjustment. It appears that some of the volatile trace elements (e.g., arsenic, selenium, and antimony) are stripped to some extent. This has implications for the potential environmental impacts of the stripper overheads and effluent streams. For example, it may be possible to reduce the amounts of some toxic trace elements that might otherwise concentrate in brines produced by downstream evaporators. However, this potential was not investigated.

- Phenols were the major organic species found in the wastewater. 2,4-dimethyl phenol was largely stripped and was found principally in the overhead condensate. Other phenols (e.g., phenol, cresol and other xylenol isomers) were only partially stripped and are found in both the effluent and overhead condensate.

- Hydrocarbon analyses of the overhead vapor were hampered by relatively high concentration of residual methyl isobutyl ketone (MIBK) from the solvent extraction process. Toluene and xylene were not detected in any of the

samples, while benzene was detected (at 1.1 ppmv) in only one set of the samples collected on charcoal. The residual solubility of MIBK in water is significant (reportedly about 2% by weight). Some other organics may be present in the MIBK layer produced as a result of condensing the stripper overhead stream. The solvent layer was not analyzed in this work.

- The presence of significant quantities of solvent vapor in the stripper overhead vapor stream has potential impacts on the downstream processes that may be used to remove H_2S and other acid gas species from this stream. The residual solvent concentration after extraction/inert gas stripping seen in this study is probably not representative of commercial operations. In a commercial extraction system more efficient solvent recovery would be practiced, not only to reduce the possibility of problems with downstream processes, but also to reduce solvent make-up requirements. However, more efficient solvent stripping would likely produce additional streams containing species stripped from the raffinate (including ammonia, hydrogen sulfide, etc.).

- Carbonyl sulfide was detected in all overhead vapor samples at concentrations ranging from 0.04 ppmv in the two-pass stripper run and from 1 to 5 ppmv in the single-pass runs. Carbon disulfide was the only other sulfur species detected (1 to 32 ppmv).

2.3 BENCH-SCALE TESTS: PERFORMANCE

- Contaminant removals consistent with the results of the laboratory-scale tests were found for ammonia, CO_2, and H_2S. Data scatter precluded the development of meaningful correlations for HCN and phenol removal as a function of the steam to influent ratio.

- Contaminant removals were found to increase with increasing steam to wastewater ratio up to 250-300 kg steam/m^3 wastewater. Higher ratios produced no statistically significant improvement in contaminant removals. There would appear to be little incentive to operate at a steam to wastewater ratio higher than about 250-300 kg/m^3.

- Overall volumetric mass transfer coefficients were calculated for steam stripping of NH_3, CO_2, and H_2S for the wastewater. For ammonia, K_La increased from 1.8 to 6.6 hr^{-1} as the liquid mass velocity increased from about 550

to 2000 kg/m^2hr. Over this same range K_La for CO_2 increased from 2.2 to 4.5 hr^{-1}. K_La for H_2S was found to be approximately constant at 0.6 hr^{-1} over this range of liquid flow rates.

2.4 REMAINING TECHNICAL QUESTIONS

This part summarizes areas where questions are currently unresolved. These technical questions fall into four general categories: solvent effects, chemical analyses, stripping run conditions, and modifications to the stripping apparatus or operating procedures.

- Solvent Effects

  What is the effect of extraction on the removal of wastewater contaminants by steam stripping? Experiments would need to be run with and without wastewater pretreatment by extraction. The effects of different solvents could also be investigated (e.g., DIPE instead of MIBK) as well as the effects of different levels of extraction. The extraction step could be carried out to give the higher residual phenol concentrations observed in commercial applications so as to lessen questions of representativeness of data.

  Does the residual solvent in the overhead stream affect results? Improved removal of residual solvent after extraction could be provided or a solvent having a lower solubility could be used in order to minimize the contamination of the stripper overhead stream.

- Chemical Analyses

  What are the quantity and composition of solid precipitating out of the stripper overheads? Such solids should be analyzed to establish their identity, and an estimate of their flow rate should be made.

  What is the composition of any separate solvent layer produced upon condensation of the overhead vapor? The solvent layer should be analyzed for additional contaminants, such as organics and trace metals.

- Stripping Run Conditions

  Does the correlation between mass transfer coefficients and liquid mass velocity maintain the same slope for other values of liquid mass velocity? Runs performed at intermediate liquid rates would be helpful in better defining the correlation between mass transfer coefficients and liquid mass velocity.

  What are the effects of two-stage stripping? Additional runs could be performed to investigate the effects of two-stage stripping on contaminant removal. This would involve adjustment of the wastewater pH to both acidic and basic levels prior to stripping.

- Modifications to Apparatus/Procedures

  What effect do methods for measuring flow rates have on results? Improvements could be made to the methods used to measure the flow rates of overhead condensate and/or vapor.

  What effect would additional temperature measurements have on results? Temperature measurements could be provided at additional locations (e.g., the overhead condensate, outside surface of the stripper column insulation).

  How would constituents lost during storage before stripping affect results? Consideration could be given to spiking the water with chemicals to make up for constituents lost during storage.

SECTION 3

EXPERIMENTAL APPROACH

3.1 RAW GAS LIQUOR COLLECTION

The gas liquor used in this study was obtained during a test run at the METC gasifier. Several drums were collected during three steady-state operating periods on November 14, 15, and 18, 1983. During this time both low-sulfur bituminous and high-sulfur coal were gasified at a system pressure of 930 kPa (135 psig). In addition the high-sulfur coal was gasified at a higher pressure, 1470 kPa (213 psig), during the sampling conducted on November 18. Circulating gas liquor in the gas cooling section of the process was sampled at system pressure using a specially-designed dissolved gas sampling apparatus (DGSA). The DGSA enabled the gas liquor to be flashed to ambient pressure at a controlled temperature. The flash temperature was controlled at 54°C (130°F) on November 14-15, and 59°C (138°F) on November 18. Flashed gas liquor was collected in new carbon steel drums with removable lids. After filling, the drums were sealed and shipped to Radian's Austin, Texas headquarters, where they were placed in refrigerated storage prior to use. The time from collection to storage was approximately seven days. The wastewater used in the stripping test program was all from the low-sulfur coal run.

At the same time the bulk samples were collected, small grab samples were obtained for determination of composition. Those parameters having short sample holding times were analyzed on site. The samples for other parameters were preserved on site and shipped to Radian's Austin, Texas laboratories for analysis. The results of the wastewater analyses at the time of collection are summarized in Appendix D.

3.2 LABORATORY-SCALE TESTS

A total of four laboratory-scale screening tests were conducted to determine the effect of initial wastewater pH on the stripping efficiency of a number of contaminants, including ammonia, sulfide, cyanide, dissolved CO_2 (alkalinity), and phenol. The results of these laboratory tests were used to help determine the initial wastewater pH used during the subsequent bench-scale tests. The equipment used in these pH-variation tests is illustrated in Figure 1. The apparatus consisted of a 1-liter distillation flask, an Allihn condenser to provide reflux, and a Fischer Milligan gas wash bottle containing 5% H_2SO_4. For each test, 800 mL of wastewater were introduced into the flask and heated using an electric heating mantle to 95-100°C. Small aliquots of the wastewater were withdrawn and the temperature recorded at 0, 15, 30, 60, 90, 120, 150, 180, and 270 minutes after the first drop of reflux was observed. The samples were analyzed for ammonia and pH. After 270 minutes the test was discontinued and the wastewater remaining in the flask was analyzed for the parameters summarized in Table 1. The solution in the gas wash bottle was also analyzed after each run for ammonia in order to provide a mass-balance check. Table 1 also provides the initial pH of the wastewater during each of the four tests performed.

For use in the laboratory stripping tests, a total of 8 L of wastewater were withdrawn from one of the drums that had been collected on November 14, 1983, and extracted using methyl isobutyl ketone (MIBK). This solvent was chosen based on the results of published studies that showed it to have the highest distribution coefficient for phenol of the solvents examined (1,2). Extractions were performed using a 2-L separatory funnel. One liter portions of the wastewater were extracted between 3 to 5 times with separate 100 mL portions of fresh solvent. For each extraction, the wastewater and solvent were shaken together for 3 minutes and allowed to separate for 5 minutes. After the final extraction, the wastewater was purged with nitrogen for 10 minutes to remove excess MIBK. All of the 1-liter portions of extracted wastewater were combined and refrigerated prior to stripping. The batch

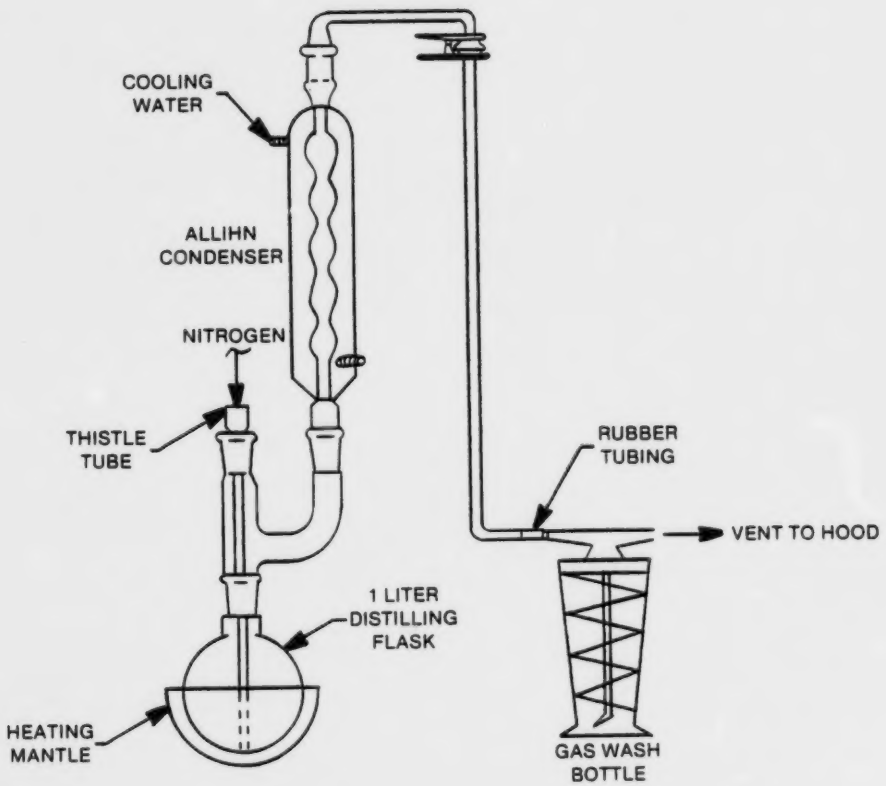

Figure 1. Apparatus used in laboratory-scale pH-variation tests.

TABLE 1. SUMMARY OF LABORATORY-SCALE WASTEWATER STRIPPING TESTS PERFORMED

- Wastewater pH before stripping:

  8.6 (after extraction): 2 tests
  9.5
  11.0

- Temperature controlled at 95-100°C by heating mantle

- Parameters analyzed before and after stripping:

  pH
  Conductivity
  Total alkalinity
  Ammonia
  Total cyanide
  Free cyanide
  Phenol
  Sulfide
  Sulfite
  Sulfate
  Thiocyanate

- Parameters analyzed during stripping:

  pH
  Ammonia

extractions reduced the total phenol concentration of the wastewater used in the laboratory-scale tests from 4000 mg/L to 6 mg/L.

For the tests in which the initial wastewater pH was adjusted, lime was added to give the desired pH. The wastewater was then filtered prior to stripping to remove any undissolved lime and precipitated solids. It was necessary to repeat the lime addition/filtration steps to the water that had been adjusted to a pH of 11 since the pH was found to have dropped after the initial precipitation.

3.3 BENCH-SCALE TESTS

A total of five bench-scale tests were conducted to obtain mass transfer data for certain dissolved gases (ammonia, carbon dioxide, hydrogen sulfide, hydrogen cyanide) and phenol and to characterize the stripper outlet streams. The tests were performed using a 0.1 m (4 inch) diameter stainless steel column packed with 1.2 m (4 feet) of 0.6 mm (1/4-inch) ceramic Intalox saddles. A schematic of the steam stripping apparatus is shown in Figure 2. Wastewater that had been previously extracted with MIBK and pH-adjusted using lime was passed through a fiber cartridge filter, preheated to 90°C in an electric water heater, and pumped into the top of the stripping column. Stripping steam from an electric steam generator was introduced into the column below the packing and passed countercurrent to the wastewater. Concentric tube heat exchangers were used to condense and cool the overhead stream and to cool the column effluent (or "bottoms"). Both the condensate and the effluent left the heat exchangers at about ambient temperature (25-30°C). Samples of the influent, effluent, overhead condensate, and overhead vapor were obtained and analyzed for the performance and environmental species of interest. Stripper operating conditions (temperature, pressure, pressure drop, and flow rates) were monitored often throughout each run and recorded every hour. Each run lasted approximately 8 hours. The principal independent variable during these tests was the steam-to-wastewater flow ratio. Table 2 summarizes conditions for each of the bench-scale tests. The last

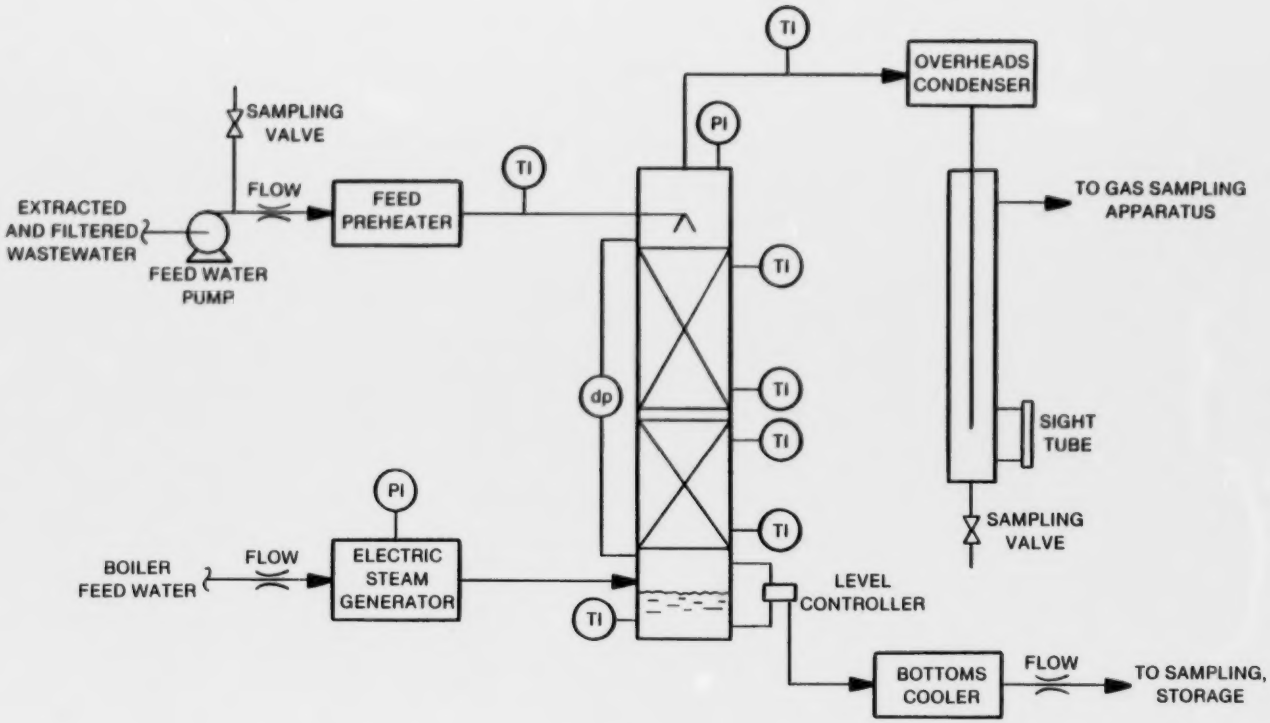

Figure 2. Bench-scale steam stripping equipment.

TABLE 2. SUMMARY OF BENCH-SCALE STEAM STRIPPING TESTS PERFORMED[a]

Run Date	Steam Flow kg/hr	Influent Flow m^3/hr	Steam/Influent kg/m^3	Influent pH	Preheat Temperature, ^oC
9/25	2.15	0.0162	133	9.0	87.3 ± 1.0
9/27	1.93	0.0065	298	9.0	90.1 ± 0.4
11/1	1.96	0.0070	282	9.1	89.6 ± 0.5
11/2	2.08	0.0045	459	9.2	89.7 ± 0.7
11/5[b]	2.08	0.0070	297	8.5	89.6 ± 1.4

[a]All runs performed using 1.2 m (4 ft) of 6 mm (1/4 inch) Intalox saddles.

[b]Run of 11/5 used previously stripped wastewater collected during runs of 9/27, 10/31, and 11/2. The 10/31 run was performed solely for the purpose of producing additional stripped wastewater.

experimental run performed (November 5, 1984) utilized wastewater as influent that had previously been stripped at the same steam-to-wastewater ratio. This was done in an attempt to simulate the effects of additional packing height on contaminant removals and distributions. It is recognized that this is not precisely what would be observed in a real column, where the wastewater would actually "see" contaminated steam. It is possible that this "backpressure" would tend to inhibit removal of strippable species, resulting in the need for more stages than observed in order to produce a given level of removal.

A total of four drums of METC gasifier wastewater were pretreated by extraction using MIBK as the solvent for use in the bench-scale tests. All of the drums used had been collected during the low-sulfur bituminous coal run of November 14-15, 1983. A 0.08 m (3 inch) diameter York-Scheibel liquid-liquid extraction column containing 9 mixing and separating stages was used at a solvent-to-feed ratio of 0.1-0.2 kg/kg. The extracted wastewater was stripped with nitrogen at ambient temperature, about 25-30^{o}C, in a 7.6 cm (3 inch) diameter stainless steel column packed with 90 cm (3 ft) of Intalox saddles in order to reduce the residual MIBK concentration prior to steam stripping. Subsequent steam stripping runs showed that significant quantities of solvent remained after this nitrogen stripping. Chem-Pro (3) reportedly uses steam stripping to remove residual (proprietary) solvent from extracted wastewater, but this also results in stripping a large fraction of the H_2S and some ammonia into the overhead solvent stream. In subsequent solvent-recovery steps these contaminants must then be separated from the solvent in order to avoid problems in downstream sulfur-recovery (e.g., Claus) operations.

The extracted wastewater was stored in nitrogen-purged drums prior to stripping. The target phenol concentration for the extraction was 100-200 mg/L; the actual performance of the extraction column was better than anticipated, with phenol levels from 10 to 60 mg/L actually obtained. The removal of phenol by steam stripping in a commercial system may be different from that observed as a result of this work because of these differences in initial phenol concentration.

SECTION 4

RESULTS OF EXPERIMENTAL RUNS

4.1 LABORATORY-SCALE TESTS

The primary purpose of the laboratory-scale stripping tests was to determine the effect of pH on the removal of ammonia and other volatile wastewater contaminants. The results were used to help select the wastewater pH to be used in the subsequent bench-scale tests. This section presents the results of the laboratory tests. The analytical data obtained for the laboratory-scale tests are given in Appendix A.

Figure 3 shows the ammonia concentration of the wastewater during the stripping runs at three pH levels (8.6, 9.6, and 11.0). As expected, increasing the initial wastewater pH results in an increase in the rate of ammonia stripping as well as a concentration reduction in the stripped wastewater. This is because the fraction of ammonia present in the free or non-ionized form, increases with increasing pH. Note that at a pH of 11 ammonia is readily lost even at room temperature, as evidenced by the low initial concentration observed for this test. Without pH adjustment, the wastewater ammonia concentration can be reduced to about 900-1000 mg/L (as N). Lower concentrations require that the pH be increased. At a pH of 11 essentially all of the ammonia can be removed by stripping. Similar results using a different sour wastewater have been reported elsewhere (4).

Figure 4 shows the effect of wastewater pH on the percentage removals achieved by stripping for several species of interest; Table 3 summarizes these results. As mentioned previously, ammonia removals increase with pH. For the remainder of the contaminants considered here, primarily dissolved acid gases, the opposite effect is observed: increasing the wastewater pH

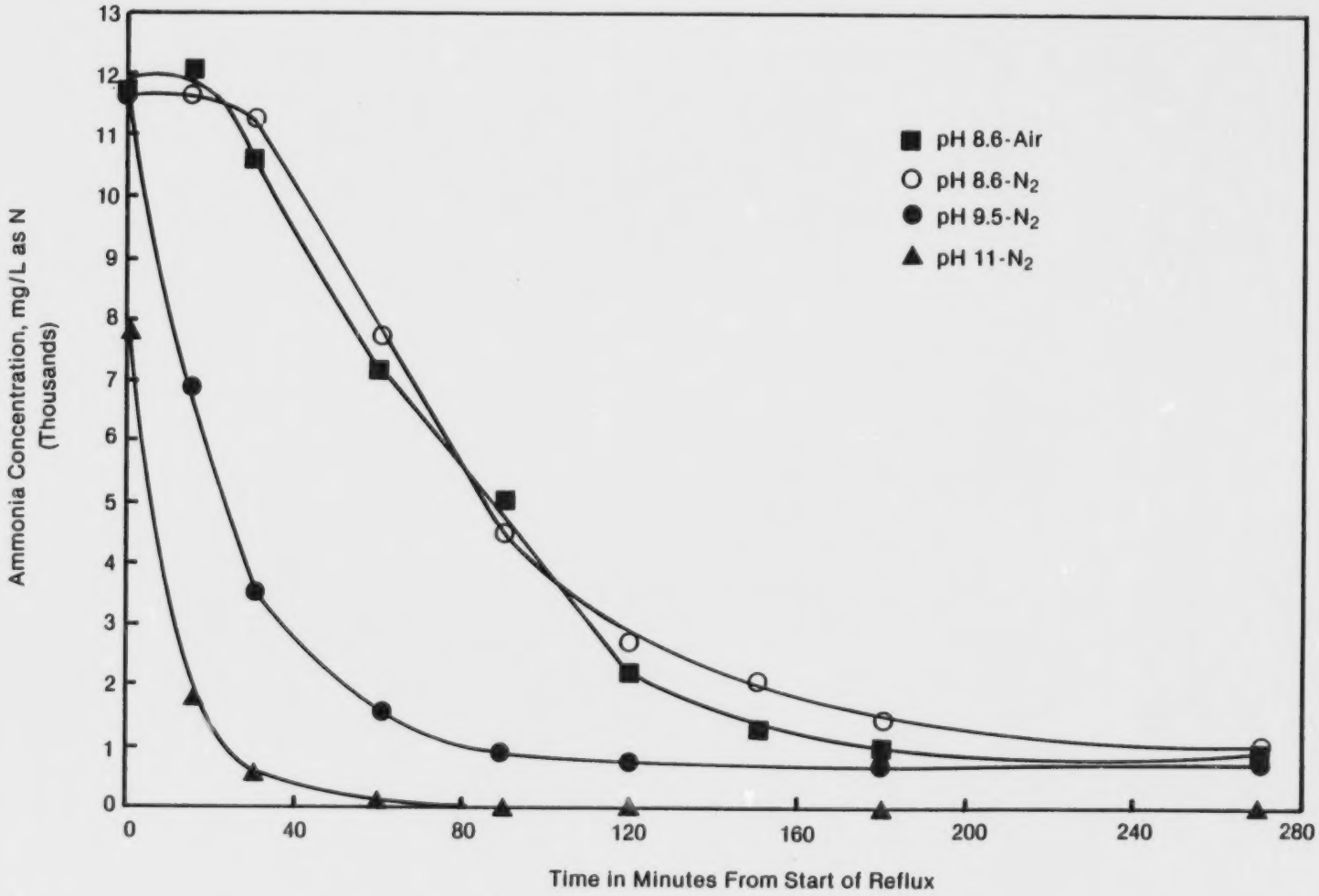

Figure 3. Ammonia concentration versus time for different initial pH levels.

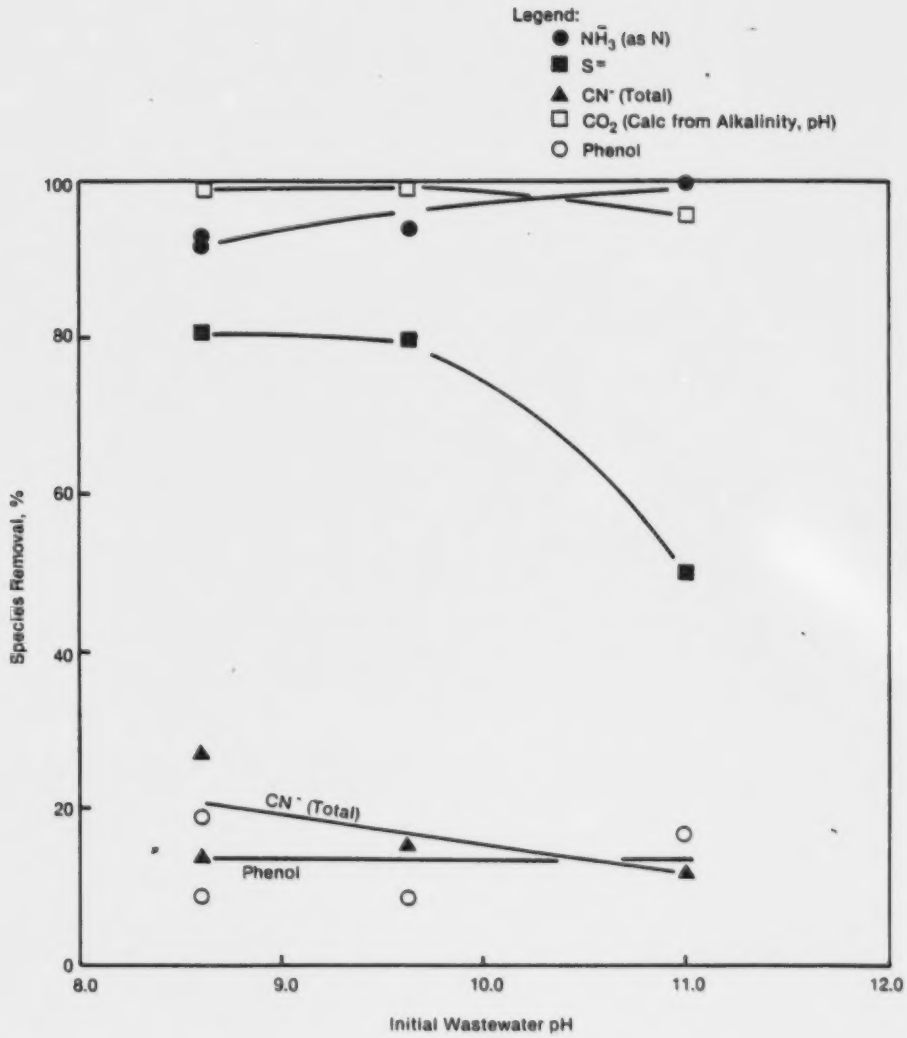

Figure 4. Species removals as a function of initial wastewater pH.

TABLE 3. SPECIES REMOVALS FROM LABORATORY STRIPPING TESTS, PERCENT

Species	Initial Wastewater pH - Stripping Gas			
	8.6 - Air	8.6 - N_2	9.6 - N_2	11.0 - N_2
Ammonia-N	91.5	93.0	94.0	99.9
Sulfide	80.6	80.6	79.6	50.0
Carbon Dioxide	99.4	99.3	99.5	96.3
Cyanide (Total)	13.5	26.9	15.4	11.5
Phenol (Total)	8.3	18.3	8.3	16.7

results in less efficient removal. Note that alkalinity (due to dissolved carbon dioxide) is readily removed; reductions greater than 99% of the initial alkalinity are achieved even at a pH of 9.6. Even at pH 11 the removal is over 96%.

A similar pattern is seen for sulfide: 80% removal can be achieved up to a pH of 9.6. Above this the removal drops off more rapidly than for CO_2, reaching 50% at pH 11. Cyanide is not efficiently stripped from this wastewater: average removals of 20% were observed at the lower pHs, falling to about 10% at pH 11. An examination of the free cyanide concentration versus total cyanide reveals that the majority of the cyanide in this wastewater at the time of the stripping tests was present in complexed forms that are not amenable to removal by stripping. It is likely that some of the cyanide originally present in the wastewater had become complexed with iron or other metals or had reacted with sulfide to form thiocyanate. Cyanide removals higher than those seen during these tests would likely occur for fresh gasifier wastewater. A small fraction (about 10-20%) of the total phenol remaining in the wastewater after pretreatment by extraction was removed by stripping. Since in these tests most of the phenol had been removed prior to stripping, it is difficult to predict what fraction of the phenol present in the untreated water might have been removable by steam stripping.

These results show that if the objective of steam stripping is to maximize ammonia removal, then the wastewater pH should be as high as is practical, up to pH 11. If, however, it is desired to also remove dissolved acid gases, lower pH levels are needed. If both ammonia and acid gas species must be removed, then two-stage stripping may be required. One way to do this would be to first maximize ammonia removal by operating at an elevated pH; the pH could then be lowered prior to the second stage where acid gas removal could be maximized.

During the tests performed at pH 8.6, significant solids buildup was observed in the overhead lines. Such deposition could lead to plugging

problems in a large scale steam stripper as the overhead stream is cooled. It was observed that adjusting the pH with lime significantly reduced the plugging problem. It is likely that the solids were an ammonium salt, such as ammonium carbonate or ammonium carbamate, however the solids were not analyzed during this experimental program. Similar solids plugging problems have been reported by other investigators (3,5). In neither of these studies were the solids analyzed, but Chem-Pro (3) suggested that they might be a salt of ammonia and hydrogen sulfide, and found that reducing the stripping steam flow rate helped alleviate the problem. Verhoff and Choi (5) cited the work of others that $(NH_4)_2S$ and carbonate precipitation are two possible causes for plugging.

Figure 5 shows the amount of base (lime, in this case) that was required to raise the pH of the extracted wastewater. For example, in order to raise the pH from approximately 8.5 to 9.5, 470 milliequivalents, meq, of lime were required per liter of wastewater. In order to go from the "as received" pH to a pH of 11 nearly 1200 meq of lime were needed. These quantities show that the unstripped water has significant buffering capacity, due to its high carbonate/bicarbonate alkalinity. It is reasonable to expect that significantly less lime would be required for pH adjustment of the wastewater following an initial stripping stage near the "as received" pH of 8.5 - 8.6. Alternatively, sodium hydroxide or another more soluble base might be used. The final choice would depend on an analysis of the costs associated with the alternatives and the effects of dissolved solids or downstream processes (e.g., biological treatment).

Based on the laboratory tests it was decided to perform the bench-scale stripping tests at a pH of 9.5. The reasons for this are as follows:

- Removals of most of the species of interest in this study are reasonably high at this pH, thereby providing the opportunity to obtain mass transfer data for several species.

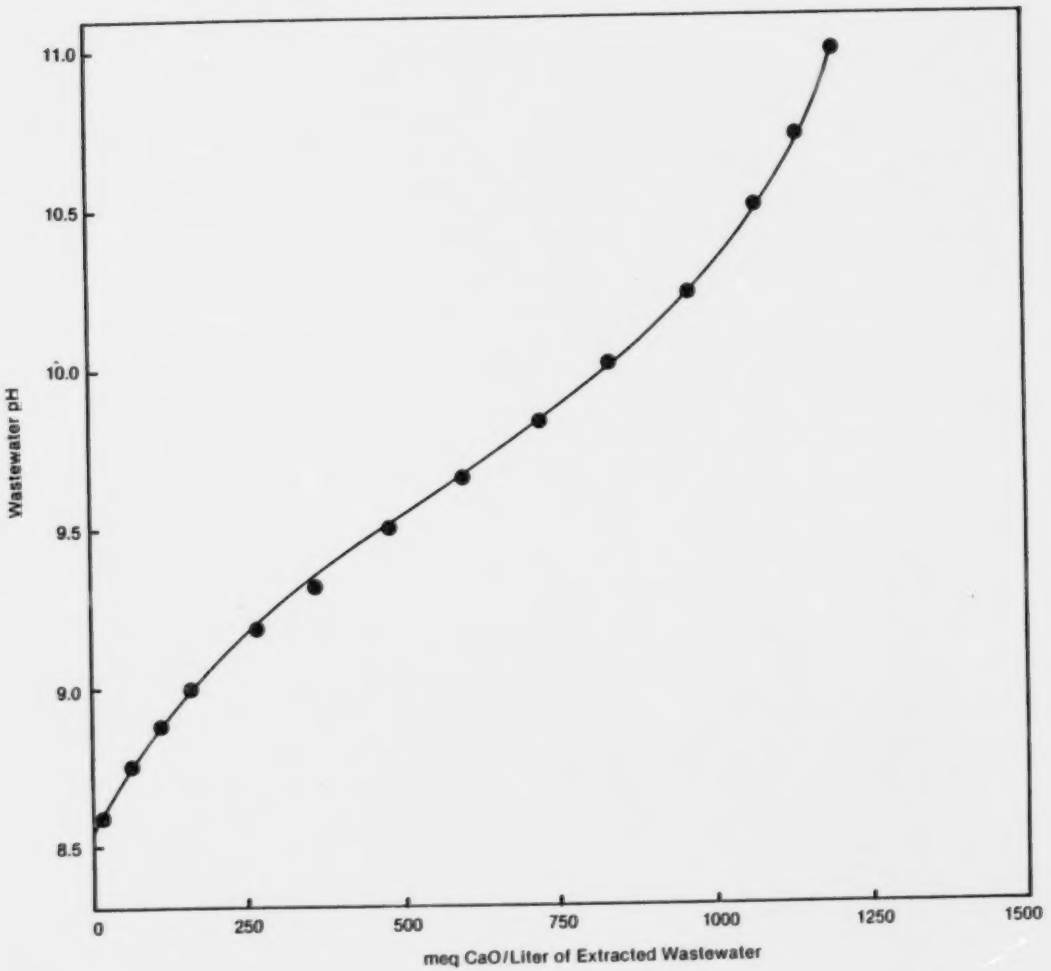

Figure 5. Titration curve for MIBK-extracted METC wastewater.

- Operation at pH 9.5 should help reduce the potential problem of condenser plugging observed at the "as received" pH during the laboratory tests.
- Rates of addition of lime are not excessive for pH adjustment from 8.5 to 9.5.

4.2 BENCH-SCALE TESTS

4.2.1 Environmental Characterization Results

During three of the five stripping test runs, grab samples of the influent, effluent, and condensate were collected at two hour intervals and composited to yield one sample of each stream for each run. The composite samples were analyzed for species of environmental interest including water quality parameters, trace elements, and extractable organics. Samples of the overhead vapors from the stripper column were also analyzed during these runs to identify major gas components, sulfur species, hydrocarbons, and volatile organics. A brief discussion of the results of these analyses is provided in this section. The detailed data are given in Appendix C.

Water quality analyses of the samples show that alkalinity, ammonia, chloride, fluoride, sulfide, cyanide, thiocyanate, and phenol are the major components of the influent. (See Table 4.) Alkalinity and ammonia are greatly reduced in the steam stripping process and are concentrated in the condensate. Sulfide, cyanide, and phenol are only slightly removed primarily due to the elevated pH of the influent. As previously mentioned, it is likely that the fresh wastewater would contain more of the cyanide in the free form. If this were the case, larger quantities of cyanide would be present in the overhead streams, with the potential for impacting downstream treatment processes. Chloride, fluoride, and thiocyanate are not steam-stripped; the concentrations of these species in the effluent are similar to those in the influent. The low concentrations found in the condensate are probably due to entrainment of small amounts of wastewater in the overhead streams.

TABLE 4. SUMMARY OF WATER QUALITY ANALYSIS OF ENVIRONMENTAL SAMPLES[a]

Parameter	Influent Average	Effluent			Condensate		
		11-1	11-2	11-5	11-1	11-2	11-5
pH (pH units)	9.0-9.2	7.21	6.95	6.59	9.51	7.35	9.21
Total Alkalinity, as $CaCO_3$	35,700-41,000	360	500	260	212,000	291,200	5,800
Ammonia as N	11,700-12,500	680	600	500	59,800	36,200	1,840
Total Cyanide	60-80	32	43	40	ND (0.5)[b]	ND (0.5)	5.2
Sulfide as S	65-145	38	37	14	69	95	16
Total Phenol	11-59	20	10	16	38	33	61
Thiocyanate	630-740	580	590	490	6.1	2.2	0.8
Chloride	810-860	810	820	810	180	150	145
Fluoride	55-64	61	57	55	ND (0.1)	0.2	ND (0.1)

[a]All values except pH expressed as mg/L (ppm).

[b]ND ( ) - Not detected (detection limits).

TABLE 5. SUMMARY OF TRACE ELEMENT ANALYSES OF COMPOSITE SAMPLES[a]

Element[b]	Influent Average	Effluent			Condensate			Detection Limit
		11-1	11-2	11-5	11-1	11-2	11-5	
Al	ND[c]	3.3	4.9	6.5	ND	ND	ND[d]	0.05
As	2.6	0.33	0.21	0.31	1.2	1.8	ND	0.06
B	23	28	25	23	ND	ND	ND	0.01
Ba	ND	0.028	0.022	0.041	ND	ND	ND	0.001
Be	ND - 0.001	0.002	0.002	0.001	ND	ND	ND	0.001
Ca	1.9	2.5	2.9	8.6	0.8	0.8	ND	0.05
Cd	ND	0.054	0.086	0.41	ND	ND	ND	0.002
Cr	ND	0.056	0.044	0.046	ND	ND	ND	0.001
Cu	ND	0.033	0.073	1.9	ND	ND	ND	0.001
Fe	39	28	29	18	0.071	ND	ND	0.008
K	9	9	9	6	7	7	ND	0.04
Mg	ND	1.4	1.6	2.4	ND	ND	ND	0.03
Mn	ND	0.002	0.010	0.034	ND	ND	ND	0.001
Mo	ND - 0.067	ND	ND	ND	0.009	0.021	ND	0.002
Na	ND - 0.66	4.1	3.1	4.1	ND	ND	ND	0.10
Ni	0.034	0.14	0.14	0.074	ND	ND	ND	0.003
P	6.4	8.4	10	10	6.7	7.8	ND	0.18
Sb	0.02 - 0.67	ND	ND	ND	0.28	0.57	ND	0.03
Se	5.6	1.4	1.6	0.34	0.13	0.44	ND	0.08
Sr	0.078	0.016	0.017	0.043	0.06	0.098	ND	0.001
Ti	ND	0.007	0.006	ND	ND	ND	ND	0.005
Tl	1	ND	ND	ND	0.74	0.96	ND	0.09
V	ND	0.013	ND	0.004	ND	ND	ND	0.003
Zn	0.17	0.13	0.19	0.25	0.21	0.12	0.17	0.003

[a] All values except pH expressed as mg/L (ppm).

[b] Ag, Co, Hg, and Pb were not detected in any of the samples. Their detection limits (mg/L) were as follows:

Ag	0.002
Co	0.006
Hg	0.03
Pb	0.08

[c] ND - Not detected.

[d] 11/5 run used effluent from previous runs as stripper feed; most of the volatile trace elements had probably already been removed as a result of previous stripping.

Composite samples were analyzed for twenty-eight elements. The results of these analyses are summarized in Table 5. Silver, cobalt, mercury, and lead were not detected in any of the samples. Aluminum, barium, cadmium, chromium, copper, magnesium, manganese, sodium, titanium, and vanadium were found in higher concentrations in the effluent than in the influent indicating that these elements may be contaminants to the system from other sources and not actually in the wastewater. In addition, several elements including arsenic, potassium, nickel, antimony, selenium, and thallium were found in the these streams but were not found in the analysis of the original wastewater. Based on a metals analysis of the lime used to elevate the wastewater pH, it appears that many of these elements may have been introduced with the lime. (See Table C-7 for the detailed analytical results for the lime.) Some of the arsenic, selenium, and antimony in the stripper influent appear to be removed by steam stripping. If this is the case, then it may be possible to use this operation to reduce the quantities of these volatile metals in downstream operations, such as evaporators or cooling towers.

Summaries of the results of the extractable organics analysis of the three environmental runs are given in Table 6. Results are averages for the three runs or are given as ranges. All of the compounds detected are phenols and appear to be steam-stripped and concentrated in the condensate.

The overhead vapor after the condenser was analyzed by a number of techniques. Tedlar bags were used for collection of major fixed gases, sulfur species, and hydrocarbons for analysis by GC methods. Ammonia and cyanide were collected by impinger sorption and analyzed by wet chemical methods. Charcoal tubes were used to collect volatile organics (including benzene, toluene, and xylene) which were analyzed by GC after extraction with carbon disulfide. The results of these analyses are summarized in Table 7.

Ranges for fixed gases showed that the major components were CO_2 and N_2 with lesser concentrations of O_2 and H_2. It appears that the higher-than-expected nitrogen and oxygen concentrations may be due to dilution of the gas

TABLE 6. SUMMARY OF EXTRACTABLE ORGANIC ANALYSES OF STEAM STRIPPER COMPOSITES[a]

Species	Influent Average	Effluent			Condensate		
		11-1	11-2	11-5	11-1	11-2	11-5
2,4-Dimethylphenol	0.7 - 1.9	ND[b]	0.3	ND	ND	1.2	0.2
Xylenol (other than 2,4 isomer)	1.1 - 1.4	0.56	0.1	ND	2.8	1.3	0.5
Phenol	2.3 - 8.7	4.9	5.0	11	47	23	38
Cresol	2.7 - 6.3	2.7	2.3	4.2	17	13	29
Pentachlorophenol	ND	ND	ND	ND	0.01	ND	ND

[a]All values as mg/L (ppm).

[b]ND - Not detected at 0.1 mg/L.

TABLE 7. SUMMARY OF RESULTS OF GAS ANALYSES OF OVERHEAD VAPORS FROM STEAM STRIPPER COLUMN

	11/1/84	11/2/84	11/5/84
Fixed Gases, (volume %)			
H_2	1.04	1.63	0.217
O_2	8.21	22.91	14.96
CO_2	43.87	ND[a] (1)	16.86
N_2	39.18	76.9	54.21
CO	0.275 - 1.35	ND (0.1)	0.115
Sulfur Species (ppmv)			
H_2S[b]	ND (0.1)	ND (0.1)	ND (0.1)
COS	1.7 - 5.3	0.927	0.04
CS_2	12 - 32	1.12	ND (0.01)
Volatile (ppmv)			
Benzene	1.1	ND (0.5)	ND (0.5)
Toluene	ND (0.5)	ND (0.5)	ND (0.5)
Xylene	ND (0.5)	ND (0.5)	ND (0.5)
Other Gases (ppmv)			
Cyanide	ND (20)	ND (20)	ND (20)
Ammonia	ND (50)	ND (50)	ND (50)

[a] ND ( ) = Not detected (detection limit).
[b] Expect that H_2S redissolved in condensate.

samples with air rather than from stripped gases. The relative concentrations of the two gases are roughly the same as those present in air. The source (or sources) of any air dilution is not known, although it may have been due to leaking connections between the system and the Tedlar gas sampling bags, residual air in the bags, other system leaks. Major sulfur species were carbonyl sulfide and carbon disulfide; hydrogen sulfide was not detected in any of the samples. It appears that the H_2S redissolved in the overhead condensate. It may be necessary to limit the amount of condensing performed in a commercial system if the steam stripper overheads are treated for acid gas removal and/or sulfur recovery, or to limit the concentrations of potentially toxic contaminants if the overhead condensate stream is to be discharged, routed to a biological oxidation unit, etc.

Benzene was the only C_1-C_6 hydrocarbon detected in the vapors. In general, the residual methyl isobutyl ketone in the wastewater was concentrated in the vapors and interfered with the detection of the other light hydrocarbons. MIBK (or other extraction solvent) in the overhead vapor and/or condensate may impact downstream treatment processes, such as sulfur recovery. For example, the Claus process is sensitive to the presence of organics; they can lead to the formation of "black" sulfur. It should be noted that much of the MIBK remaining in the stripper influent is due to the inefficient nitrogen-stripping of the wastewater following extraction used during this study, and may not be representative of commercial applications in which more severe solvent stripping conditions are used. For example, Chem-Pro uses steam stripping to remove residual extraction solvent (3).

Ammonia and cyanide were not detected in the overhead vapors but were associated with the waters found in the condensate. Cyanide was primarily in the bound form and was not steam strippable. The detection limits for these species are high, primarily due to the low volume of gas available for sampling. These species (especially ammonia) likely redissolved in the overhead condensate to a significant extent.

4.2.2 Component Removals

Steam stripping is a useful wastewater treatment technique for reducing the concentration of a number of dissolved gases such as ammonia, carbon dioxide, hydrogen sulfide, hydrogen cyanide, and some volatile organic compounds. Table 8 summarizes the contaminant removals obtained during the bench-scale stripping runs, using extracted and pH-adjusted METC gasifier wastewater. The primary operating variable during these runs was the steam-to-influent ratio, also shown in the table. Figures 6, 7, and 8 present the contaminant removals as a function of the steam-to-influent ratio for ammonia, carbon dioxide, and sulfide. Cyanide and phenol (total) removals were not plotted due to excessive data scatter which produced some anomalous results, especially for phenol. More phenol was found in the effluent than in the influent for some tests, leading to negative removals. The cyanide data exhibited no meaningful trends due to excessive scatter.

From the plots of ammonia, carbon dioxide, and sulfide removal, it can be seen that the percentage of each of these contaminants removed increased as the steam/influent ratio increased, up to a ratio of about 250-300 kg steam/m^2 wastewater. Any additional increase in the steam/influent ratio results in no statistically significant increase in contaminant removal. Since increases in the steam/influent ratio translate directly into added energy requirements for steam generation, there seems to be little incentive for operating the stripping unit above 250 - 300 kg steam per cubic meter of wastewater. In practice, the steam/influent ratio would be determined by a number of factors, including trade-offs between steam costs and costs of separation stages (packing height or trays).

The final run (11/5) was performed using wastewater that had been previously stripped at the same steam/influent ratio. The wastewater pH was not adjusted prior to the second pass. Additional contaminant removal was observed for all of the contaminants, although there was considerable data scatter, leading to large sample deviations. The scatter was due to

TABLE 8. COMPONENT REMOVAL SUMMARY FOR BENCH-SCALE STRIPPING TESTS[a]

Run Date	Steam/Influent kg/m^3	Influent pH	% Removal				
			NH_3	CO_2	Sulfide	Total Cyanide	Total Phenols
9/25	133 ± 7	9.03 ± 0.05	83.6 ± 3.8	93.3 ± 0.5	30.9 ± 17.9	18.9 ± 4.2	-5.2 ± 5.4
9/27	298 ± 31	9.02 ± 0.15	94.3 ± 1.5	98.3 ± 0.6	17.7 ± 38.7	23.8 ± 13.6	44.9 ± 9.7
11/1	282 ± 44	9.14 ± 0.03	91.6 ± 4.5	98.6 ± 0.2	65.1 ± 9.1	59.7 ± 3.5	-72.8 ± 28.6
11/2	459 ± 49	9.17 ± 0.06	95.0 ± 1.7	99.0 ± 0.1	69.4 ± 16.6	16.6 ± 41.1	4.2 ± 31.8
11/5[b]	297 ± 34	8.45 ± 0.04	31.0 ± 25.6	81.6 ± 5.1	-7.6 ± 51.8	23.7 ± 21.0	46.7 ± 12.4

[a]Values shown are mean ± sample standard deviation. All runs performed using 1.2 m (4 ft) of packing.

[b]11/5 run performed using effluent collected from previous stripping runs at similar steam/influent ratios.

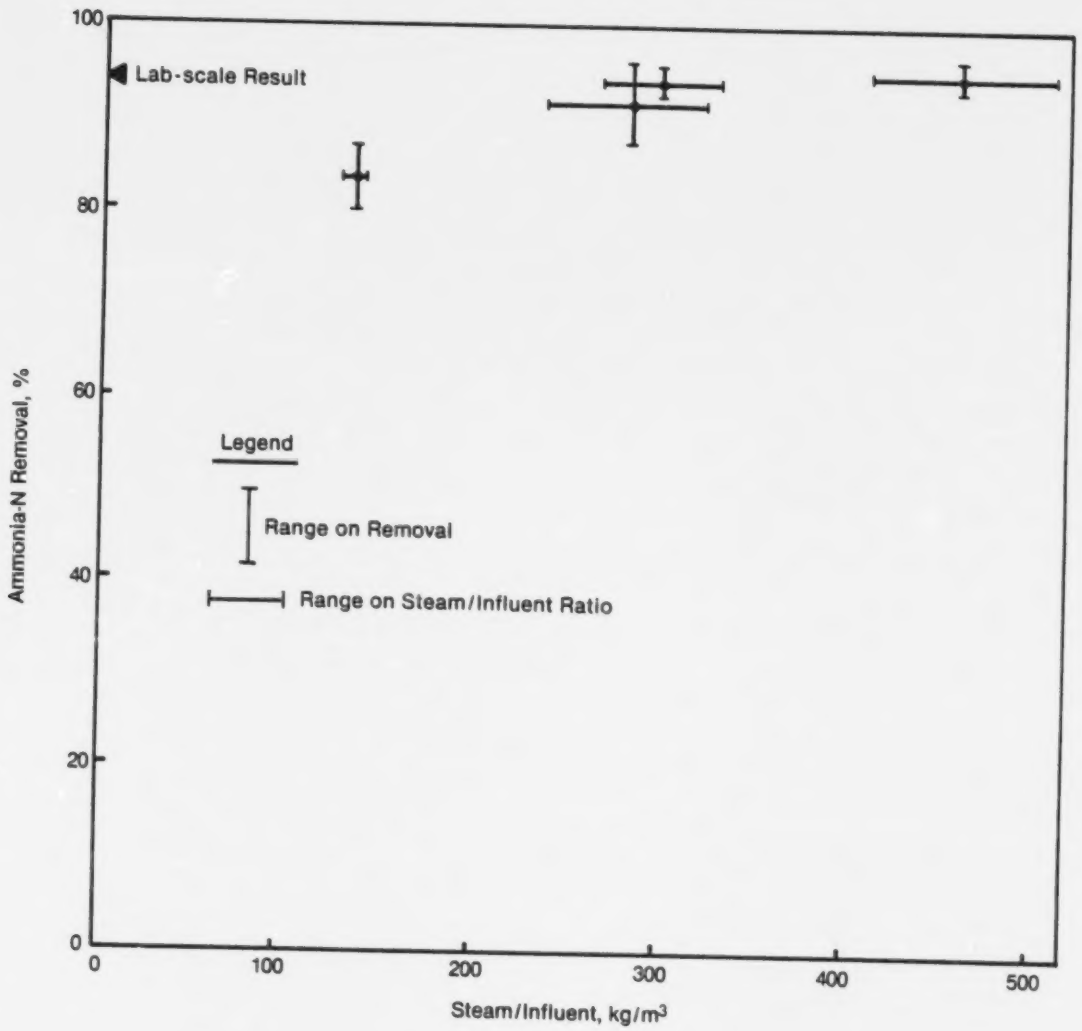

Figure 6. Ammonia removal versus steam/influent ratio.

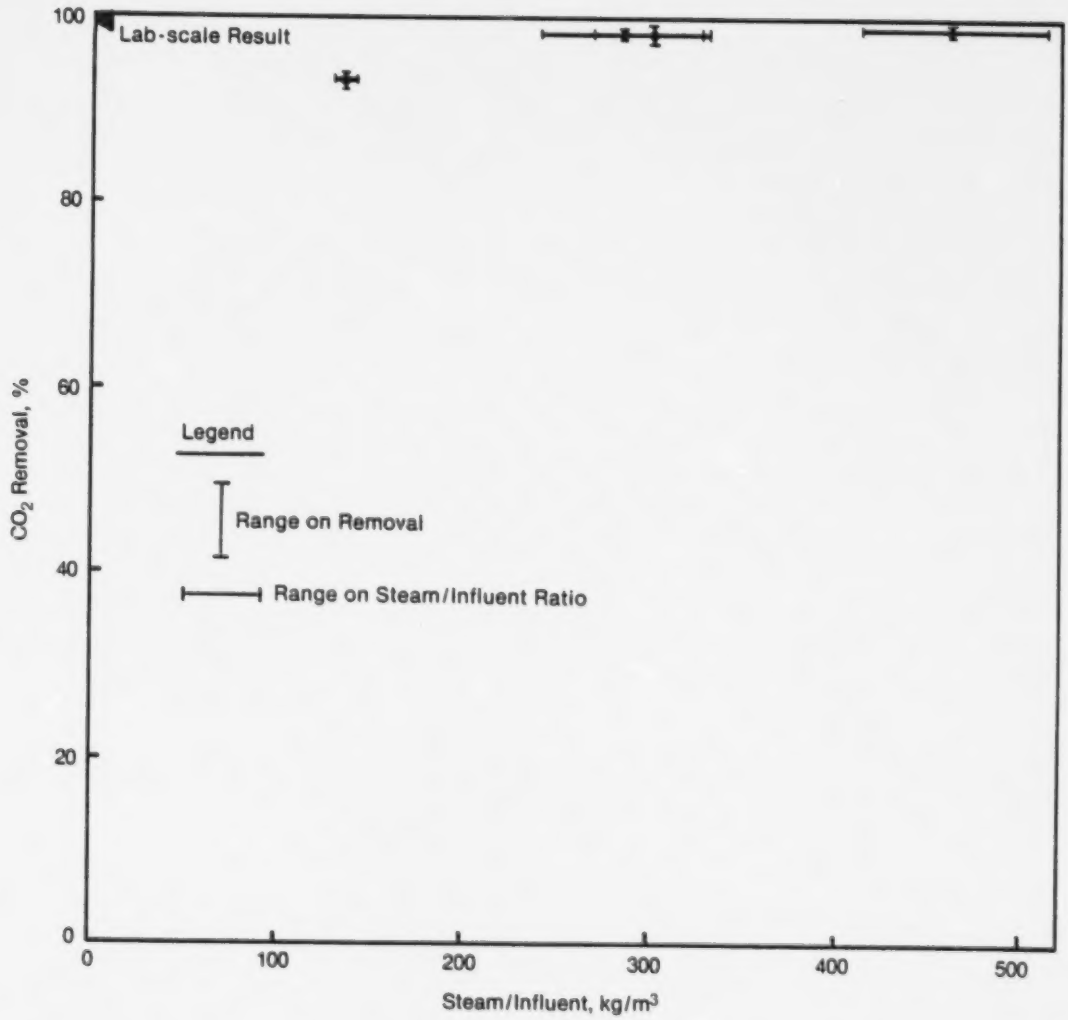

Figure 7. Carbon dioxide removal versus steam/influent ratio.

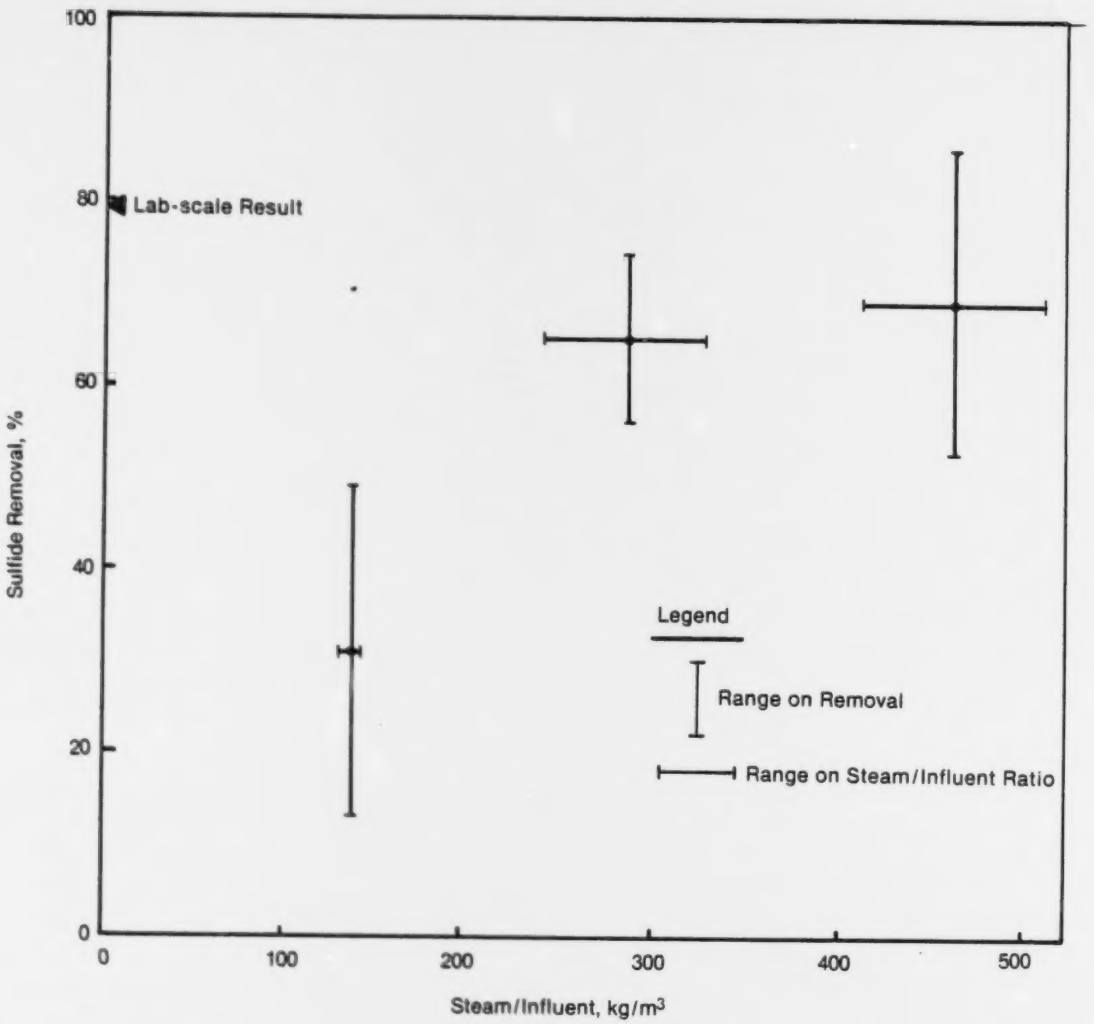

Figure 8. Sulfide removal versus steam/influent ratio.

difficulties inherent in analyzing for low concentrations coupled with uncertainties in steam flow rate measurements. When the removals obtained from both stages of stripping were combined for ammonia, carbon dioxide, and sulfide, it was found that the overall removals compared quite well with the ultimate removals achieved during the laboratory stripping runs for the same pH range. This observation indicates the value of the laboratory tests as a screening technique for determining achievable contaminant removals as a function of pH.

4.2.3 Mass Transfer Coefficients

Overall liquid phase volumetric mass transfer coefficients (K_La) were developed for ammonia, carbon dioxide, and hydrogen sulfide. It was not possible to obtain K_La values for hydrogen cyanide and phenol owing to the high degree of scatter in the data. Removals of cyanide and phenol achievable by steam stripping of this wastewater were low. Eighty to ninety per cent of the mass of these species present in the influent were found in the stripper effluent during the laboratory-scale tests. The cyanide was present in non-strippable fixed forms and the phenol volatility appeared to be relatively low under the stripping conditions used in these tests.

The procedure for estimating mass transfer coefficients from the experimental data is described in the following text. The equation used for calculating K_La values involves the overall number of liquid phase transfer units, NTU_L, which as can be seen in Appendix D, requires the following inputs:

- Mole fractions of the species of interest in the influent and effluent. These were calculated based on chemical analyses and assuming that the total number of moles was equal to the sum of the contributions due to water, ammonia, carbon dioxide, and hydrogen sulfide. Contributions of other species were ignored since they were present in lower concentrations.

- Mole fractions of the given species that would be present at equilibrium with the vapor leaving the stripper prior to condensation. Vapor concentrations were calculated by

forcing mass balances for water, ammonia, carbon dioxide, and hydrogen sulfide. Equilibrium concentrations were estimated using Henry's Law constants published for the system H_2O - NH_3 - CO_2 - H_2S (6).

- Additional inputs included liquid mass velocity, and the packing height. Liquid mass velocities for the various runs were taken as the average of the influent and effluent flow rates divided by the column cross-sectional area. The packing height, 1.2m, was constant for all runs. Heat losses were assumed to be negligible.

Table 9 summarizes the mass transfer coefficients obtained by the above procedure for ammonia, carbon dioxide, and hydrogen sulfide. They are plotted as a function of the liquid mass velocity, L, in Figures 9, 10, and 11, respectively. Regression techniques were used to obtain least squares curve fits of K_La as a function of L. The least squares straight lines of K_La as a function of L are shown on the figures, together with coefficient of determination, r^2, for each line. A value of r^2 close to 1.0 indicates an excellent correlation: r^2 tells what fraction of the variation in K_La can be attributed to the linear relationship with L. A value of $r^2 = 0.0$ would indicate that K_La is independent of L. For NH_3 and CO_2 a linear relationship between K_La and L appears to exist over the range of L studied. Data from runs made at intermediate L-values would be useful in further defining the relationship between K_La and L. For H_2S, K_La appear to vary only slightly over the range of L studied.

The K_La values calculated for NH_3 and CO_2 behaved as expected; they increased with increasing liquid mass velocity. Similar behavior was obtained by Radian in a series of steam stripping runs performed using wastewater from a fluidized-bed gasifier (7). The values of K_La obtained in this program are in the same range as those obtained previously, although quantitative agreement cannot be expected due to differences in wastewater pH and contaminant concentrations.

K_La values for H_2S were found to be relatively constant over the range of liquid mass velocities studied, with the exception of the value obtained for

TABLE 9. MASS TRANSFER COEFFICIENTS CALCULATED FROM STEAM STRIPPING DATA

Run Date	L, kg/m^2 hr	(K_La) NH_3, hr^{-1}	(K_La) CO_2, hr^{-1}	(K_La) H_2S, hr^{-1}
9/25	1,980	6.6	4.5	0.7
9/27	736	2.2	2.4	0.1
11/1	807	2.2	2.8	0.7
11/2	548	1.8	2.2	0.6

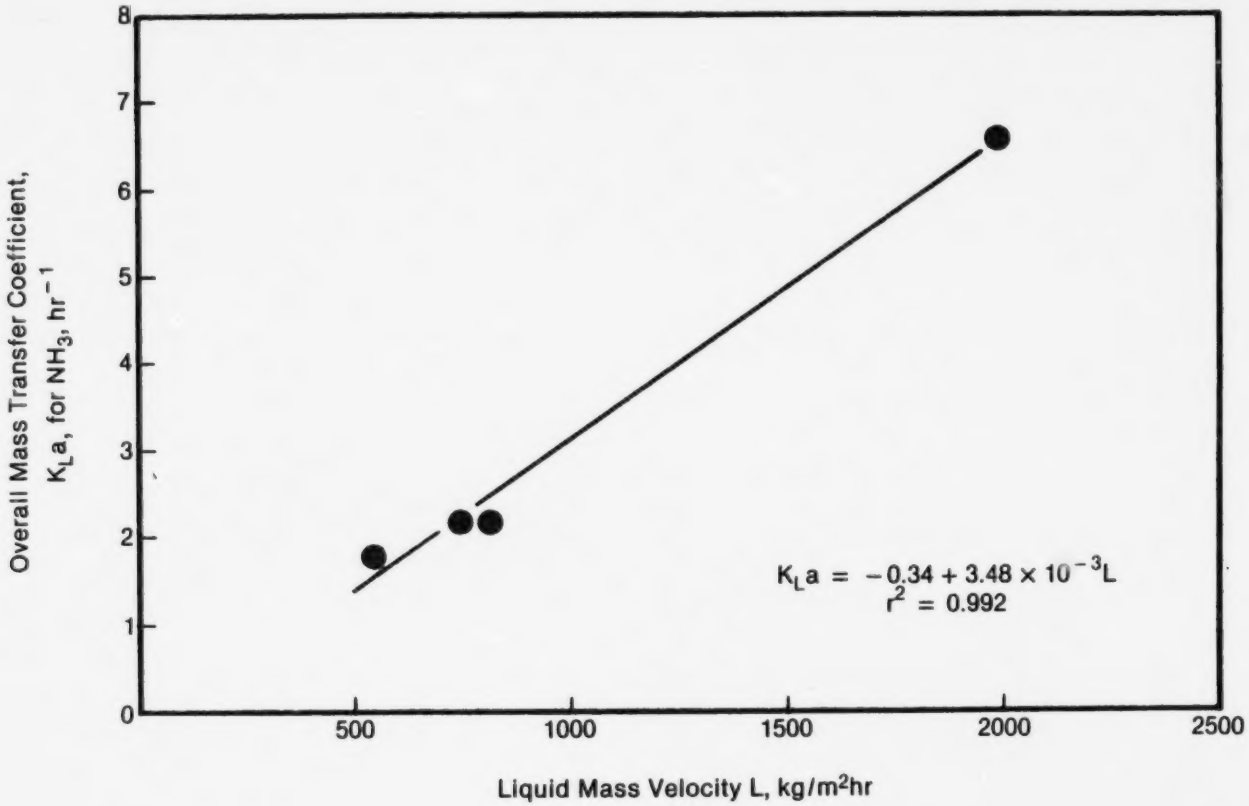

Figure 9. Overall mass transfer coefficient for NH_3 as a function of liquid mass velocity.

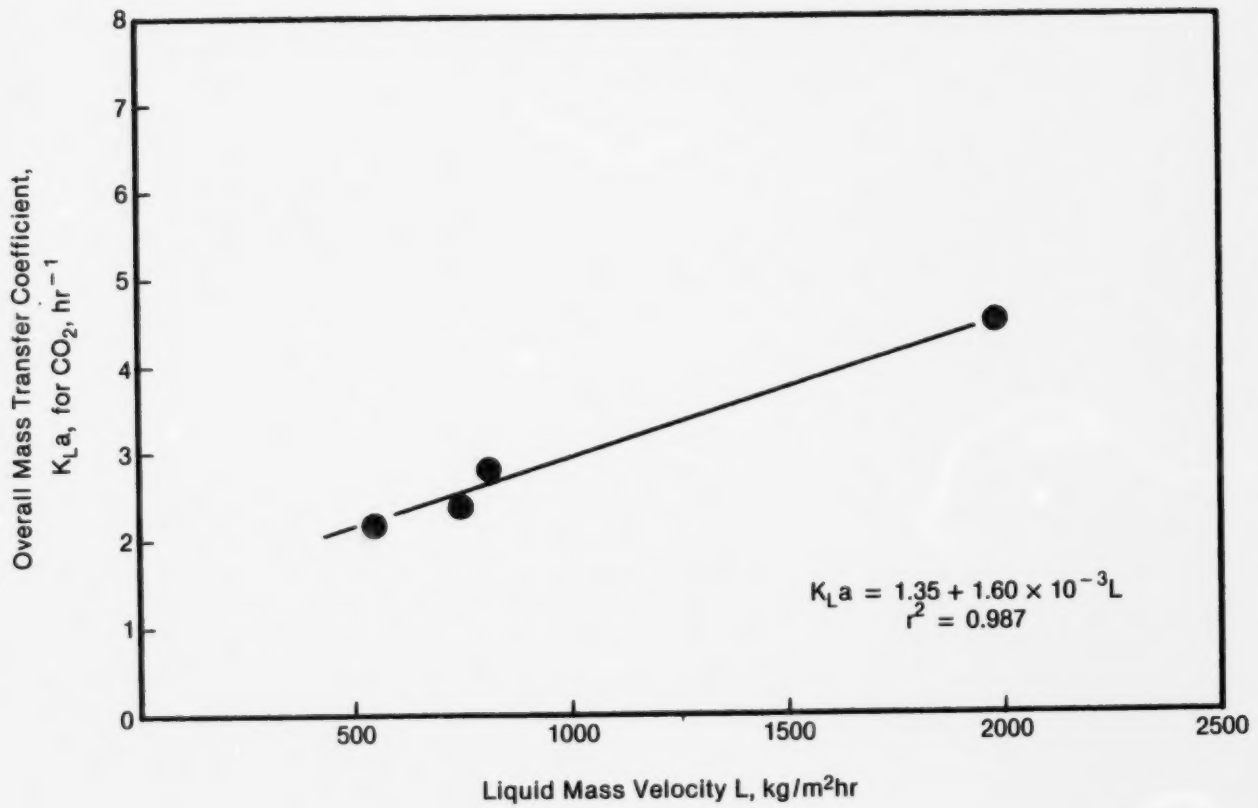

Figure 10. Overall mass transfer coefficient for CO_2 as a function of liquid mass velocity.

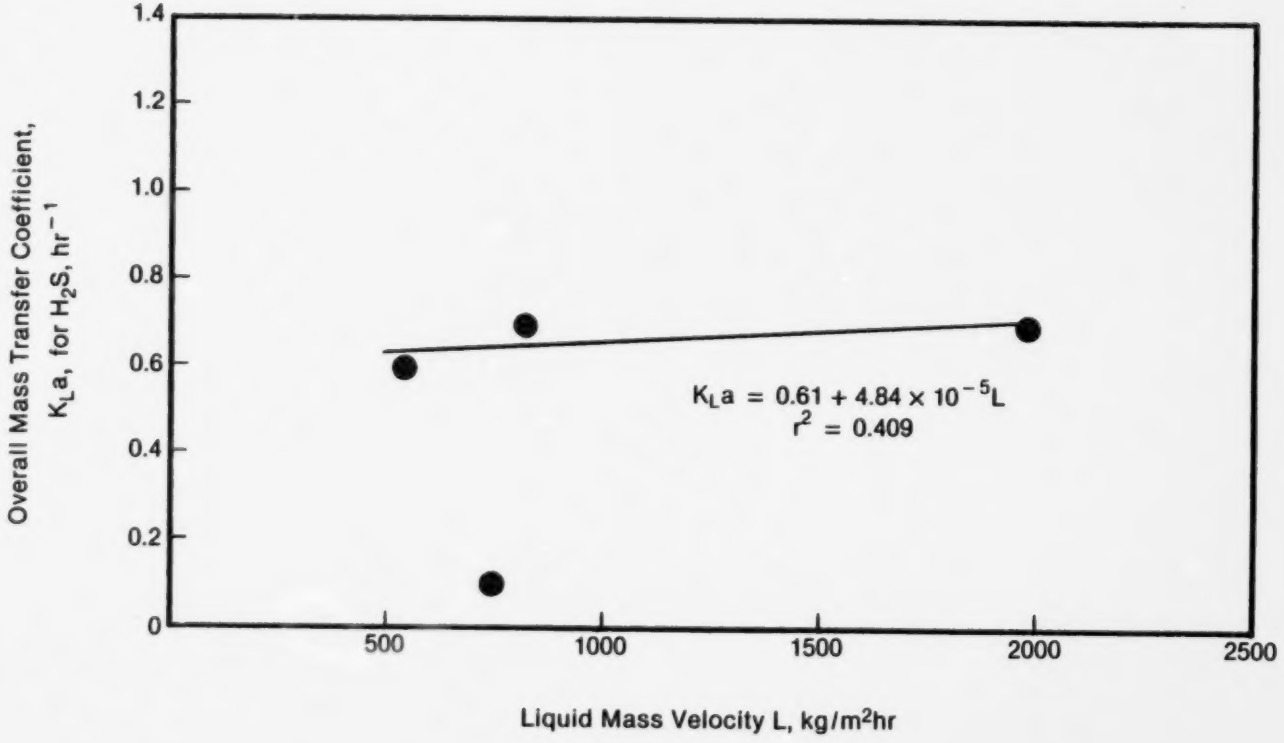

Figure 11. Overall mass transfer coefficient for H_2S as a functionof liquid mass velocity.

the run of 9/27. The sulfide concentrations obtained for this run appear anomalous, and they lead to apparent negative component removals as seen previously. This point is felt to be an outlier. H_2S does not appear to be as readily strippable from this wastewater as other contaminants at the pH selected (9-9.5) based on the low K_La values obtained. If the objective of stripping were to maximize sulfide removal, a lower pH would be required. A two-stage stripping system would be necessary in order to maximize the removal of both ammonia and acid gases.

4.3 LIMITATIONS AND EXTRAPOLATION

As Bolles and Fair (8) point out, the currently available models used in the design of packed towers can often be "disappointingly unreliable". Large safety factors are necessary in order to insure a successful design. Towers may therefore be taller and have larger diameters (and thus be more expensive) than are actually needed to effect the stripping required. In addition, extrapolating the results of small diameter tests to very large installations may be difficult. Results from steam stripping tests performed using other sources of sour water, although similar, show some differences due to differences in wastewater contaminant concentrations and chemistries (3,4,5). Pilot scale testing is probably prudent.

With this caution in mind, the remainder of this section discusses how the results obtained in this study may be applied to other situations.

4.3.1 Other Packings

Column diameters may be calculated for other packing materials by using the proper packing factor for the packing shape and size under consideration. The packing factors are readily available in the literature as well as from vendors. As far as the extrapolation of overall mass transfer coefficients to other packings is concerned, extensive data are available for the mass transfer behavior of different sizes and types of packings for specific systems

(e.g., absorption of CO_2 in a sodium hydroxide solution). The Norton Co. (9) has published such a compilation for several packings. An estimate of mass transfer for other systems can be obtained by multiplying the known mass transfer coefficient for the system of interest by the ratio of the mass transfer coefficients for the tabulated system. Care must be exercised to use data which are valid for the flow rates of interest since mass transfer coefficients also depend on liquid and gas superficial mass flow rates. In general, for a given packing type, the mass transfer coefficient decreases as the nominal packing size increases, at a given flow rate.

4.3.2 Different Flow Rates

Calculation of column diameters at flow rates different from those used in the present program is straightforward: the correlation used is described in Appendix D.

The effect of changes in flow rate on mass transfer coefficients can be accounted for by the ratio technique described above. In general, the following effects of changes in flow rates are observed (8):

- An increase in the superficial liquid flow rate, L, produces an increase in the mass transfer coefficient; and
- An increase in the superficial gas flow rate, G, greatly increases the rate of mass transfer for soluble gases. At low values of G, mass transfer can be diffusion limited; mass transfer is enhanced by turbulent transport, which becomes more important as G increases.

4.3.3 Different Coals

Wastewaters produced during the gasification of different coals will likely show large differences in the concentrations of strippable contaminants. Gasification of coals with a higher nitrogen content may produce wastewater with more ammonia and cyanide; higher sulfur coals may produce wastewaters with more sulfide. These higher inlet concentrations will require

more stripping in order to achieve the same effluent contaminant levels. This could mean more packing (or trays) or higher steam to feed ratio or both. Adjustment of the feed pH may also be necessary, since only the non-ionized portion of a given contaminant is removed by stripping. Since the interactions among all the species in the wastewater of interest determine the extent to which a given contaminant is ionized, some testing of the wastewater to obtain mass transfer data is probably prudent. In the absence of such testing, it may be necessary to make the assumption that the mass transfer behavior of the new wastewater is similar to that presented here, and that any difference in the required column packing height can be accounted for in the NTU calculations.

4.3.4 Trayed Columns

The design of trayed columns is different from that of continuous contactors such as packed columns. Such units have discrete contacting stages, and lend themselves to design by stage-by-stage equilibrium calculations for mass and energy transfer, corrected by tray efficiency. Numerous texts are available which describe the design of trayed columns, and the details will not be presented here.

The concept of transfer unit height (HTU) may be used, however, to estimate the number of theoretical or equilibrium stages required to achieve a given stripping efficiency. The concept which links packed bed height and number of theoretical stages is the so-called height equivalent of a theoretical plate, or HETP. The following mathematical expression shows how HTU_L and HETP are related (8):

$$HETP = \frac{\gamma \ln}{1-\gamma} \; HTU_L \qquad (4\text{-}1)$$

where $$\gamma = \frac{\text{slope of equilibrium line, } dy_e/dx}{\text{slope of operating line, } L_M/G_M}$$

L_M = liquid molar flow rate

G_M = gas molar flow rate.

In order to estimate the number of theoretical stages needed, the HETP is calculated as above; the packed column height can then be divided by HETP to give the number of theoretical stages.

4.3.5 Fresh Wastewater

The wastewater used in this study differed in at least two significant ways from "fresh" fixed-bed gasifier wastewaters. First, the majority of the phenol had been removed for this test series by extraction with MIBK. In commercial applications, other solvents (e.g., diisopropyl ether, DIPE) may be used and phenol removals are typically not as complete. It is possible that additional phenol may be removed by stripping in commercial systems.

Second, the cyanide content of the wastewater used in these tests was primarily present in fixed forms, and some had reacted with sulfide to form thiocyanate. It is likely that higher cyanide removals would be achieved with fresh wastewater, resulting in higher cyanide concentrations in the overhead streams.

SECTION 5

DATA VALIDATION

This section summarizes the results of the procedures used to validate the data obtained during the experimental runs. Section 5.1 presents the results of the laboratory-scale tests and Section 5.2 presents the results for the bench-scale stripping tests. QA/QC procedures are presented in detail in Appendix D.

5.1 LABORATORY-SCALE TESTS

The laboratory-scale tests were performed primarily to determine the effects of varying wastewater pH prior to stripping on the removal of various contaminants. The procedures used to validate the data from these tests included the duplication of one set of tests, calculation of ammonia partitioning, and the comparison of observed ammonia removals with the predictions of a free ammonia correlation.

5.1.1 Results of Duplicate Runs

Two stripping runs using wastewater at the "as received" pH (8.6) were performed. The first run was carried out by aspirating air through the wastewater using a vacuum pump, while in the second run nitrogen gas was sparged through the contents of the flask. The ammonia concentration versus time for these two runs is presented in Figure 12. No significant differences were observed between the two runs. The reasons for small differences may be due to a number of factors including:

- differences in temperature (control was by Variac, and it was difficult to exactly duplicate conditions from run to run);

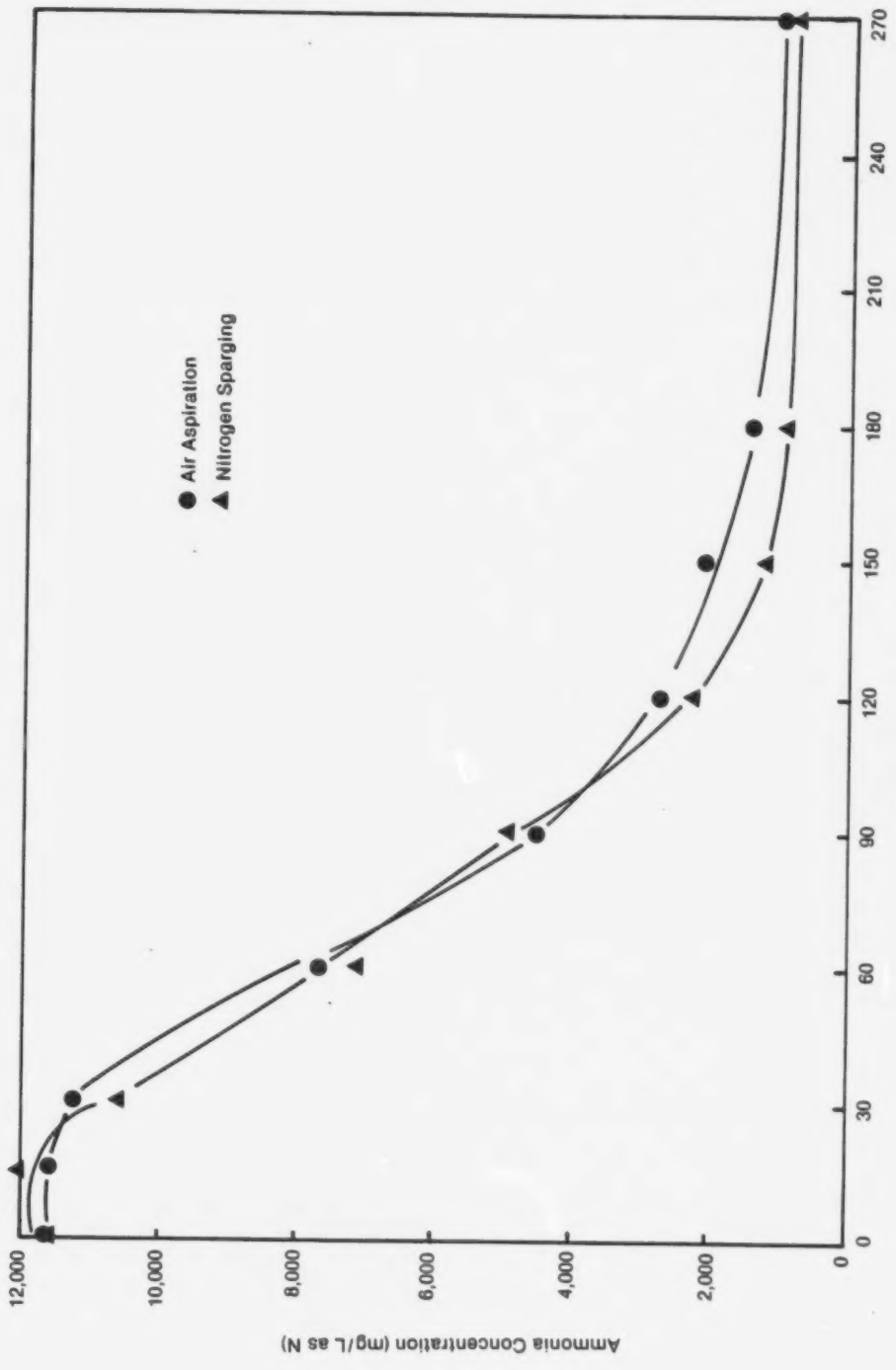

Figure 12. Results of duplicate lab-scale tests at pH = 8.6.

- rate of gas contacting (it may be that the nitrogen sparging was more efficient in stripping due to higher rate of bubbling than the air);
- accuracy of the analytical procedure. For this type of test the reproducibility is considered to be quite good.

5.1.2 Ammonia Partitioning

For each laboratory-scale test, analyses were performed of the ammonia concentration in the wastewater prior to stripping, in stripped wastewater remaining in the flask, and in the gas wash bottle solution. The mass of ammonia in each solution was calculated based on these concentrations and measured liquid volumes. The results of these calculations are presented in Table 10.

During the runs performed using wastewater at the "as received" pH (8.6), a significant quantity of crystalline solids was observed in the lines after the condenser. It is likely that these solids consisted of ammonium salts, such as ammonium carbonate or ammonium carbamate. Very few solids were present after the run at pH 9.5, and none were observed after the run at pH 11. The desire to minimize solids deposition was a significant factor in the decision to adjust the wastewater pH to 9.5 for the bench-scale tests.

5.1.3 Comparison With Literature Correlation

In aqueous solutions, free ammonia exists in equilibrium with the ammonium ion and hydroxide ion as illustrated in Equation 5-1:

$$NH_3 \cdot nH_2O(aq) \rightleftharpoons NH_4^+ + OH^- + (n-1)H_2O \qquad (5\text{-}1)$$

The fraction of total ammonia that exists as free ammonia is highly dependent on the pH, ionic strength, and temperature of the solution. This fraction can be calculated using an equation derived by Willingham (10) for the percent free ammonia in aqueous solution:

TABLE 10. AMMONIA PARTITIONING IN LABORATORY-SCALE TESTS

Test Conditions[a]	Ammonia (mg)			Solids[b]
	Original	After Stripping	Overhead Trap	
Original pH (8.6), Air	9810	620	4550	H
Original pH (8.6), N_2	9810	750	6280	H
pH 9.5	8740	530	6670	M
pH 11	6220	8	5375[c] 364	L

[a]In all runs except the first, nitrogen was used to purge the distillation flask.

[b]Solids deposition in equipment lines following condenser
H = heavy
M = medium
L = light or none

[c]Two impingers in series were used in this test only. The total amount found is the sum of the two values.

$$\text{Percent free ammonia} = \frac{100}{1 + 10^{(pK_a - pH)}} \qquad (5\text{-}2)$$

The dissociation constant has been correlated as a function of temperature using compiled literature data from 0 to 50°C (11):

$$pK_a = 0.09018 + 2729.92/(T + 273.2) \qquad (5\text{-}3)$$

where, T = temperature, °C.

The percentages of free ammonia predicted by the correlation using the temperature of the contents of the distillation flask are compared with the observed removals for the various experimental runs in Table 11. The experimental values are in good agreement with the values predicted for free ammonia, especially since the stripping temperatures were outside the original range of the correlation. This serves to emphasize the fact that only free ammonia is strippable.

5.2 BENCH-SCALE TESTS

Data from the bench-scale steam stripping tests were evaluated using the following techniques: duplicate test runs, duplicate analyses, component mass balances, and estimation of column heat losses. Each of these is discussed below.

5.2.1 Duplicate Test Runs

The steam stripping tests performed on 9/27 and 11/1 were performed to provide an indication of the reproducibility of the results from one test run to another. Table 12 presents the results of these runs for five principal chemical components. The values shown in the table are averages for the runs; values for each individual sample are given in Appendix B.

TABLE 11. COMPARISON OF CALCULATED AND MEASURED AMMONIA REMOVAL

Initial pH	Flask Temp, °C[a]	Calculated % Free NH_3[a,b]	Measured % NH_3 Removed[c]
8.6	94 ± 5	92.2 ± 1.6	93.3
8.6	94 ± 6	92.1 ± 1.9	93.0
9.5	98 ± 3	99.3 ± 0.1	94.0
11.0	100 ± 1	99.97	99.9

[a] Mean ± sample standard deviation.

[b] Free ammonia calculated by the use of Equation 5-2.

[c] $$\text{Measured \% removal} = 1 - \frac{\text{Final mass of } NH_3 \text{ in flask}}{\text{Initial mass of } NH_3 \text{ in flask}} \times 100\%$$

TABLE 12. COMPARISON OF RESULTS FROM DUPLICATE BENCH-SCALE STEAM STRIPPING RUNS[a]

Component	Stream	Run 9/27 Steam/Influent$_3$= 298 ± 31 kg/m^3	Run 11/1 Steam/Influent$_3$= 282 ± 44 kg/m^3
Ammonia (mg/L)	Influent	11,870 ± 290	11,750 ± 870
	Effluent	720 ± 90	956 ± 386
	Condensate	64,830 ± 18,450	64,130 ± 10,390
Total Alkalinity (mg/L)	Influent	35,650 ± 250	35,900 ± 500
	Effluent	640 ± 150	500 ± 0
	Condensate	178,000 ± 7,000	200,000 ± 8,000
Total Cyanide (mg/L)	Influent	71 ± 2	80 ± 1
	Effluent	58 ± 2	32 ± 2
	Condensate	2.8 ± 0.2	<0.5
Sulfide (mg/L)	Influent	65 ± 14	108 ± 3
	Effluent	51 ± 9	39 ± 6
	Condensate	38 ± 22	69 ± 23
Phenol (mg/L)	Influent	55 ± 0	11.5 ± 0.5
	Effluent	33 ± 2	20 ± 5
	Condensate	49 ± 0	38 ± 8

[a]Values shown are mean ± sample standard deviation.

In general, the results for ammonia and total alkalinity are in good agreement with each other. Influent concentrations for these species were within 1% of each other for the two runs. The agreement between the two runs for total cyanide, sulfide, and phenol is not as good. Differences in influent concentrations can be accounted for because drums of wastewater obtained at different times from the METC gasifier were used. Phenol concentrations for the two runs probably differ for this reason as well as possible changes in extraction operations for the two drums. Reasons for discrepancies in apparent removals for these species are not as clear.

5.2.2 Duplicate Analyses

Approximately 10% of the sample analyses were performed in duplicate in order to determine analytical variability. Table 13 summarizes the results of these duplicate analyses. The data are given in more detail in Appendix D. The table shows that the best analytical reproducibility was obtained for total alkalinity, thiocyanate, sulfite, ammonia, and conductivity; agreement between duplicate analyses averaged better than $\pm$5%. Parameters showing wider analytical variability included COD, total cyanide, sulfide, and phenol. The phenol variability was especially high, averaging $\pm$16% for the five sets of samples chosen for duplication.

5.2.3 Component Mass Balances

Mass balances were performed using the measured flow rates of the various input and output streams and component concentrations. Where possible, statistically determined means and sample standard deviations were used to give ranges of flow rates and concentrations. The total mass of a given species accounted for in the output streams divided by the mass of that species in the influent defines the mass balance closure for that species. Table 14 shows the results of this evaluation for the overall mass of H_2O (as water and steam), ammonia, carbon dioxide, sulfide, total cyanide, and phenol. In general, the overall balance was found to be within estimated error of the

TABLE 13. SUMMARY OF DUPLICATE ANALYSES FROM BENCH-SCALE TESTS

Parameter	Number of Duplicates	Mean Relative Error, %[a]	Range of Relative Error[a]
Conductivity	4	4.3	0 - 8.7
Total Alkalinity	2	1.2	0.5 - 1.9
NH_3-N	17	3.7	0 - 16.7
COD	2	12.1	4.8 - 19.3
Total CN^-	4	6.7	0 - 14.3
SCN^-	2	1.7	0 - 3.3
Sulfide	3	7.2	4.4 - 9.3
Sulfite	3	2.6	0 - 6.3
Phenol	5	16.0	13.0 - 24.1

[a]Relative error calculated as $\frac{\text{Larger value - smaller value}}{\text{smaller value}} \times 100\%$

TABLE 14. COMPONENT MASS BALANCE SUMMARY FROM BENCH-SCALE TESTS

Run Date	Mass Balance Closure, Percent (Out/In x 100%)[a]					
	Overall	NH_3	CO_2	Sulfide	Total Cyanide	Total Phenols
9/25[b]	100 ± 10	118 ± 57	104 ± 57	76 ± 23	80 ± 4	113 ± 6
9/27	83 ± 8	88 ± 31	75 ± 8	93 ± 47	77 ± 14	68 ± 11
11/1	85 ± 10	81 ± 23	69 ± 10	43 ± 12	39 ± 5	217 ± 40
11/2	98 ± 11	115 ± 42	106 ± 14	57 ± 31	84 ± 41	197 ± 46
11/5	84 ± 15	108 ± 34	133 ± 16	133 ± 63	79 ± 22	98 ± 15

[a]Values shown are mean ± sample standard deviation.

[b]For this run only, no measurement of overhead condensate flow rate was taken; forced overall balance and used calculated overhead condensate mass to calculate remaining balances.

measurement techniques used. It was necessary to force a balance for the 9/25 run due to lack of measurements on the overhead condensate flow rate. The standard deviations calculated for the component balances include both stream flow and concentration variations; for some runs these were found to be quite large. The stream having the largest standard deviation was generally found to be the overhead condensate. For this reason, calculations required for subsequent estimation of mass transfer coefficients were based on forced mass balances using the difference between influent and effluent compositions.

The phenol balances for the runs of 11/1 and 11/2 indicated about twice as much phenol in the outlet streams than the influent. This may be due to incomplete separation of extracted wastewater and solvent in the pretreatment of wastewater prior to stripping. Care was taken during sample analysis not to include material from any solvent layer that was present in some influent and overhead condensate samples. It is possible that the residual solvent contained phenol that was not accounted for in the influent samples and which remained in the effluent after stripping, since the solvent was much more volatile than the phenol. Much better mass balance closure was observed for the 11/5 run which utilized previously stripped wastewater; the residual solvent had been removed during the initial stripping run, eliminating the difficulty described above in obtaining representative samples of influent and condensate.

5.2.4 Stripping Column Heat Loss Estimation

Heat losses may be a significant source of error in the analysis of results obtained using a small diameter stripping column. Accounting for such losses rigorously requires solving simultaneous differential energy and mass balances in a packed column. The calculations are greatly simplified if heat losses are small enough to be ignored.

An estimate of heat loss from the column was performed assuming the following:

- the column is an isothermal cylinder,
- end effects are negligible, and
- there is negligible resistance to heat transfer due to the column's stainless steel walls.
- ambient temperature during the stripping runs was estimated at $55^{\circ}F$ ($13^{\circ}C$).

The rate of loss of heat by conduction through the column insulation was assumed equal to that lost by the outside surface of the insulation due to convection and radiation:

$$Q_{cd} = Q_{cv} + Q_r \qquad (5\text{-}4)$$

Expressions were written for each of the terms in equation 5-4. The result was an equation which had as its only unknown quantity the outside surface temperature of the insulation. This equation was solved by trial and error and the resulting temperature was plugged back into the expression for conductive heat loss to arrive at a heat loss rate per unit length of the column. The overall column height was then multiplied by this number to arrive at the final estimated column heat loss. The estimated rate of heat loss was compared with the overall rate of enthalpy into the column, which was calculated using steam tables and measured input flow rates and temperatures. The results of these calculations are summarized in Table 15. The heat loss was estimated to be between 2.7 to 4.3 percent of the total enthalpy input. Therefore, heat loss effects were assumed to be negligible in the calculation of mass transfer coefficients.

TABLE 15. ESTIMATED STRIPPING COLUMN HEAT LOSS VERSUS ENTHALPY OF INPUT STREAMS

Run Date	Calculated Enthalpy Input, kJ/hr[a]	Estimated Heat Loss, kJ/hr[b]	Estimated Loss As Percent of Input
9/25	11,600 ± 400	310	2.7 ± 0.1
9/27	7,610 ± 370	310	4.1 ± 0.2
10/31	8,120 ± 1,110	310	3.8 ± 0.5
11/1	7,880 ± 780	310	3.9 ± 0.4
11/2	7,270 ± 550	310	4.3 ± 0.3
11/5	8,190 ± 600	310	3.8 ± 0.3

[a](Mass flow rate of preheated wastewater x wastewater specific enthalpy) + (Mass flow rate of steam x steam specific enthalpy)

Example: Run 9/25

Enthalpy In = 16.13 ± 0.34 kg/hr x 365.5 ± 4.2 kJ/kg
+ 2.15 ± 0.08 kg/hr x 2,676.4 kJ/kg
= 11,600 ± 400 kJ/hr

[b]Heat loss by conduction = $\frac{2\pi L k_m (T_1 - T_2)}{\ln (D_2/D_1)}$

$$= \frac{2\pi \times 2.29\ m \times 0.100\ \frac{kJ}{hr\text{-}m^3\text{-}^oC} \times (102\text{-}22)^oC}{\ln \left(\frac{16.5}{11.4}\right)}$$

= 310 kJ/hr

SECTION 6

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APPENDIX A

LABORATORY-SCALE STRIPPING DATA TABLES

TABLE A-1. ANALYSES OF ALIQUOTS TAKEN DURING LABORATORY STRIPPING TESTS[a]

Test ID	Test Parameter	Initial	Time (minutes) from Start of Reflux								
			0	15	30	60	90	120	150	180	270
Original pH (8.6) N_2 purge	Temp., °C			89	86.5	92.5	97	99	98.5	97.5	
	NH_3N, mg/L		11,600	11,700	11,260	7,730	4,540	2,690	2,100	1,410	1,040
	pH, pH units			9.29	9.42	9.49	9.44	9.21	9.10	8.76	7.25
Original pH (8.6) air aspiration	Temp, °C			87	87.5	93	96	97.5	98	99.5	99
	NH_3N, mg/L		11,600	12,100	10,580	7,140	4,970	2,220	1,210	940	870
	pH, pH units			9.11	9.37	9.55	9.53	9.27	8.66	7.96	5.95
pH 9.5 N_2 purge	Temp, °C		90	92	95.5	99	99.5	99.5	--[b]	99	99
	NH_3N, mg/L	10,900	--	7,900	4,620	2,110	1,110	1,110	--	760	740
	pH, pH units	9.62	--	9.61	9.42	8.17	8.88	8.68	--	6.62	5.23
pH 11.0 N_2 purge	Temp, °C		95	98	99.5	100	100	100.5	100.5	100.5	--
	NH_3N, mg/L	7,770	5,360	1,720	520	73	20	20	7	--	--
	pH, pH units	11.00	10.24	9.84	9.48	9.11	9.25	9.40	9.66	9.67	--

[a]Aliquots taken from reflux flask.

[b] -- means no data.

TABLE A-2. ANALYSES OF WASTEWATER BEFORE AND AFTER LABORATORY STRIPPING TESTS

Component[a]	Before Stripping	After Stripping			
	Extracted Wastewater	Original pH (8.6) air	Original pH (8.6) N_2	pH Adjusted Runs pH (9.5)	pH (11.0)
pH (pH units)	8.64	5.97	7.15	6.08	9.84
Conductivity (μmhos/cm at 25°C)	40,400	4,620	4,340	3,050	8,980
Total Alkalinity as $CaCO_3$	40,200	210	270	199	2,840
Ammonia as N	12,300	830	860	740	8.3
Total Cyanide	52	45	38	44	46
Free Cyanide	1.59	1.12	0.44	0.94	0.49
Total Phenol	6	5.5	4.9	5.5	5.0
Sulfide as S	108	21	21	22	54
Sulfite as SO_3	70	153	117	94	30
Sulfate as SO_4	ND (25)[b]	ND (25)	ND (25)	ND (25)	120[c]
Thiocyanate	660	710	700	690	720

[a]All results as mg/L unless indicated otherwise in parentheses beside the component.

[b]ND ( ) = Not detected (detection limit).

[c]Appears to be due to oxidation of other sulfur species.

APPENDIX B

BENCH-SCALE STEAM STRIPPING TESTS
PERFORMANCE DATA TABLES

TABLE B-1. STEAM STRIPPER OPERATING CONDITIONS FOR RUN OF 9/25/84[a]

Flow Rates:	
Influent, m^3/h	0.0162 ± 0.0003
Steam, kg/h	2.15 ± 0.08
Effluent, m^3/h	0.0164 ± 0.0005
Overhead Condensate, m^3/h	-
Overhead Vapor, L/h	-
Steam/Influent Ratio, kg/m^3:	133 ± 7
System Temperatures, °C:	
Preheated Influent	87.3 ± 1.0
Stripper Overhead Vapor	92.0 ± 1.4
Stripper Packing Sections (top to bottom)	95.3 ± 2.5
	97.8 ± 2.5
	99.0 ± 1.8
	99.8 ± 2.1
Stripper Bottoms	87.3 ± 3.4
Packing Height, m:	1.2

[a]Values shown are mean ± sample standard deviation.

TABLE B-2. PERFORMANCE CHARACTERIZATION OF STEAM STRIPPER INFLUENT
STEAM/INFLUENT RATIO = 133 kg/m^3 AT 1.2 M PACKING HEIGHT 9/25/84

COMPONENT	SAMPLING TIME OF DAY (hrs) 1600	1800	1930	MEAN
pH (pH units)	9.03	9.08	8.99	9.03
CONDUCTIVITY (umhos/cm at 25 C)	40900	40600	40500	40700 +/-200
AMMONIA as N	11600	11800	12000	11800 +/-200
TOTAL ALKALINITY as CaCO3	-	41000	-	
TOTAL CYANIDE	-	69	-	
FREE CYANIDE	-	0.75	-	
PHENOL	-	59	-	
SULFIDE as S	-	78	-	
SULFITE as SO3	-	98	-	
SULFATE as SO4	-	<25	-	
THIOCYANATE	-	640	-	
COD as O2	-	6780	-	
TOC as C	-	6090	-	

a All results as mg/L unless indicated otherwise in parentheses beside the component.

b - Means not analyzed

TABLE B-3. PERFORMANCE CHARACTERIZATION OF STEAM STRIPPER EFFLUENT
STEAM/INFLUENT RATIO = 133 kg/m^3 AT 1.2 M PACKING HEIGHT 9/25/84

COMPONENT	SAMPLING NIME OF DAY (hrs) 1600	1800	1930	MEAN
pH (pH units)	9.17	9.04	9.06	9.09
CONDUCTIVITY (umhos/cm at 25 C)	7660	7060	6800	7170 +/-440
AMMONIA as N	2200	1720	1690	1870 +/-290
TOTAL ALKALINITY as CaCO3	-	2740	-	
TOTAL CYANIDE	-	55	-	
FREE CYANIDE	-	0.86	-	
PHENOL	-	61	-	
SULFIDE as S	-	51	-	
SULFITE as SO3	-	46	-	
SULFATE as SO4	-	<25	-	
THIOCYANATE	-	640	-	
COD as O2	-	3200	-	
TOC as C	-	1100	-	

a All results as mg/L unless indicated in parentheses beside the component.

b - Means not analyzed

TABLE B-4. PERFORMANCE CHARACTERIZATION OF STEAM STRIPPER CONDENSATE
STEAM/INFLUENT RATIO = 133 kg/m^3 AT 1.2 M PACKING HEIGHT 9/25/84

COMPONENT	SAMPLING TIME OF DAY (hrs) 1600	1800	1930	MEAN
pH (pH units)	9.18	9.50	9.34	9.34
CONDUCTIVITY (umhos/cm at 25 C)	265000	300000	310000	292000 +/-190000
AMMONIA as N	48700	97200	100000	82000 +/-23600
TOTAL ALKALINITY as CaCO3	-	346000	-	
TOTAL CYANIDE	-	<0.5	-	
FREE CYANIDE	-	<0.5	-	
PHENOL	-	29	-	
SULFIDE as S	-	52	-	
SULFITE as SO3	-	17	-	
SULFATE as SO4	-	<5	-	
THIOCYANATE	-	52	-	
COD as O2	-	-	-	
TOC as C	-	38600	-	

a All results as mg/L unless indicated in parentheses beside the component.

b - Means not analyzed

TABLE B-5. STEAM STRIPPER OPERATING CONDITIONS FOR RUN OF 9/27/84[a]

Flow Rates:	
Influent, m^3/h	0.0065 ± 0.00042
Steam, kg/h_3	1.93 ± 0.08
Effluent, m^3/h	0.0060 ± 0.0003
Overhead Condensate, m^3/h	0.00095
Overhead Vapor, L/h	12
Steam/Influent Ratio, kg/m^3:	298 ± 31
System Temperatures, °C:	
Preheated Influent	90.1 ± 0.4
Stripper Overhead Vapor	99.1 ± 1.5
Stripper Packing Sections (top to bottom)	100.3 ± 1.4
	101.7 ± 1.1
	102.1 ± 1.3
	102.0 ± 1.3
Stripper Bottoms	84
Packing Height, m:	1.2

[a]Values shown are mean ± sample standard deviation.

TABLE B-6. PERFORMANCE CHARACTERIZATION OF STEAM STRIPPER INFLUENT
STEAM/INFLUENT RATIO = 298 kg/m^3 AT 1.2 M PACKING HEIGHT 9/27/84

COMPONENT	SAMPLING TIME OF DAY (hrs) 1140	1240	1340	1530	1655	1730	MEAN
pH (pH units)	8.91	8.96	9.15	8.93	9.26	8.93	9.02
CONDUCTIVITY (umhos/cm at 25 C)	38500	38500	38700	40000	37200	39500	38700 +/-1000
AMMONIA as N	12000	11900	11500	11600	12300	11900	11900 +/-300
TOTAL ALKALINITY as CaCO3	-	-	35400	-	35900	-	35600
TOTAL CYANIDE	-	-	73	-	69	-	71
FREE CYANIDE	-	-	0.99	-	0.59	-	0.79
PHENOL	-	-	55	-	55	-	55
SULFIDE as S	-	-	81	-	56	-	69
SULFITE as SO3	-	-	101	-	68	-	84
SULFATE as SO4	-	-	<25	-	<25	-	<25
THIOCYANATE	-	-	620	-	640	-	630
COD as O2	-	-	7210	-	7630	-	7420
TOC as C	-	-	6440	-	6430	-	6440

a All results as mg/L unless indicated in parentheses beside the component.

b - Means not analyzed

TABLE B-7. PERFORMANCE CHARACTERIZATION OF $_3$ STEAM STRIPPER EFFLUENT
STEAM/INFLUENT RATIO = 298 kg/m^3 AT 1.2 M PACKING HEIGHT 9/27/84

COMPONENT	SAMPLING TIME OF DAY (hrs)						
	1140	1240	1340	1530	1650	1730	MEAN
pH (pH units)	7.81	7.44	7.62	7.61	8.10	8.17	7.8
CONDUCTIVITY (umhos/cm at 25 C)	5200	4520	4090	4450	4900	5460	4770 +/-510
AMMONIA as N	700	640	810	690	820	880	720 +/-110
TOTAL ALKALINITY as CaCO3	–	–	530	–	740	–	640
TOTAL CYANIDE	–	–	56	–	59	–	58
FREE CYANIDE	–	–	2.2	–	2.4	–	2.3
PHENOL	–	–	31	–	34	–	32
SULFIDE as S	–	–	61	–	48	–	54
SULFITE as SO3	–	–	42	–	19	–	30
SULFATE as SO4	–	–	<25	–	<25	–	<25
THIOCYANATE	–	–	590	–	660	–	630
COD as O2	–	–	3240	–	3120	–	3180
TOC as C	–	–	940	–	1030	–	1460

a All results as mg/L unless indicated in perentheses beside the component.

b – Means not analyzed

TABLE B-8. PERFORMANCE CHARACTERIZATION OF STEAM STRIPPER CONDENSATE
STEAM/INFLUENT RATIO = 298 kg/m^3 AT 1.2 M PACKING HEIGHT 9/27/84

COMPONENT	SAMPLING TIME OF DAY (hrs) 1140	1240	1340	1530	1650	1730	MEAN
pH (pH units)	9.22	9.13	9.52	8.85	9.44	9.10	9.22
CONDUCTIVITY (umhos/cm at 25 C)	270000	304000	141000	206000	15600	169000	239000 +/-64000
AMMONIA as N	88000	86700	99200	63500	53800	54900	64800 +/-1800
TOTAL ALKALINITY as CaCO3	-	-	184300	-	155900	-	178000
TOTAL CYANIDE	-	-	2.9	-	2.6	-	2.8
FREE CYANIDE	-	-	0.32	-	0.37	-	0.34
PHENOL	-	-	49	-	49	-	49
SULFIDE as S	-	-	16	-	60	-	38
SULFITE as SO3	-	-	19	-	10	-	14
SULFATE as SO4	-	-	<5	-	<5	-	<5
THIOCYANATE	-	-	3.9	-	4.5	-	4.2
COD as O2	-	-	3600	-	4240	-	3920
TOC as C	-	-	24600	-	24300	-	24400

a All results as mg/L unless indicated in parentheses beside the component.

b - Means not analyzed

TABLE B-9. STEAM STRIPPER OPERATING CONDITIONS FOR RUN OF 11/01/84[a]

Flow Rates:	
Influent, m^3/h	0.0070 ± 0.0002 m^3/h
Steam, kg/h	1.96 ± 0.26 kg/h
Effluent, m^3/h	0.0067 ± 0.0005 m^3/h
Overhead Condensate, m^3/h	0.0009 m^3/h
Overhead Vapor, L/h	-
Steam/Influent Ratio, kg/m^3:	282 ± 44
System Temperatures, °C:	
Preheated Influent	89.6 ± 0.5
Stripper Overhead Vapor	99.1 ± 2.1
Stripper Packing Sections (top to bottom)	100.6 ± 1.5 102.6 ± 0.7 102.3 ± 0.9 102.8 ± 0.7
Stripper Bottoms	86
Packing Height, m:	1.2

[a]Values shown are mean ± sample standard deviation.

TABLE B-10. PERFORMANCE CHARACTERIZATION OF STEAM STRIPPER INFLUENT
STEAM/INFLUENT RATIO = 282 kg/m^3 AT 1.2 M PACKING HEIGHT 11/01/84

COMPONENT	SAMPLING TIME OF DAY (hrs) 1100	1300	1400	1500	1700	1800	MEAN
pH (pH units)	9.12	9.13	9.20	9.12	9.12	9.17	9.14
CONDUCTIVITY (umhos/cm at 25 C)	40600	40000	41200	40000	39000	40200	40200 +/-700
AMMONIA as N	12700	11100	11000	10800	12600	12300	11800 +/-900
TOTAL ALKALINITY as CaCO3	-	-	35400	-	-	36400	35900
TOTAL CYANIDE	-	-	80	-	-	79	80
FREE CYANIDE	-	-	0.98	-	-	2.6	1.8
PHENOL	-	-	11	-	-	12	12
SULFIDE as S	-	-	100	-	-	110	105
SULFITE as SO3	-	-	120	-	-	110	115
SULFATE as SO4	-	-	<25	-	-	<25	<25
THIOCYANATE	-	-	720	-	-	760	740
COD as O2	-	-	17100	-	-	17700	17400
TOC as C	-	-	7930	-	-	6340	7140

a All results as mg/L unless indicated in parentheses beside the component.

b - Means not analyzed

TABLE B-11. PERFORMANCE CHARACTERIZATION OF STEAM STRIPPER EFFLUENT
STEAM/INFLUENT RATIO = 282 kg/m^3 AT 1.2 M PACKING HEIGHT 11/01/84

COMPONENT	SAMPLING TIME OF DAY (hrs) 1100	1300	1400	1500	1700	1800	MEAN
pH (pH units)	8.71	9.06	7.55	9.05	8.29	7.47	8.34
CONDUCTIVITY (umhos/cm at 25 C)	7960	7230	5310	5850	5420	5080	6140 +/-1180
AMMONIA as N	1480	1630	690	970	760	670	1040 +/-420
TOTAL ALKALINITY as CaCO3	-	-	500	-	-	500	500
TOTAL CYANIDE	-	-	32	-	-	32	32
FREE CYANIDE	-	-	4.3	-	-	1.8	3.1
PHENOL	-	-	24	-	-	16	20
SULFIDE as S	-	-	33	-	-	44	38
SULFITE as SO3	-	-	130	-	-	130	130
SULFATE as SO4	-	-	<25	-	-	<25	<25
THIOCYANATE	-	-	570	-	-	590	580
COD as O2	-	-	3020	-	-	2780	2900
TOC as C	-	-	1060	-	-	770	920

a All results as mg/L unless indicated in parentheses beside component.

b - Means not analyzed

TABLE B-12. PERFORMANCE CHARACTERIZATION OF STEAM STRIPPER CONDENSATE
STEAM/INFLUENT RATIO = 282 kg/m^3 AT 1.2 M PACKING HEIGHT 11/01/84

COMPONENT	SAMPLING TIME OF DAY						MEAN
	1100	1200	1400	1500	1530	1730	
pH [pH units]	9.73	9.74	9.79	9.60	9.51	9.42	9.63
CONDUCTIVITY [umhos/cm at 25 C]	218000	215000	19100	183000	193600	198000	199800 +/-13900
AMMONIA as N	74700	72700	51600	56700	54700	55200	60900 +/-10000
TOTAL ALKALINITY as CaCO3	-	-	208000	-	19200	-	200000
TOTAL CYANIDE	-	-	<0.5	-	<0.5	-	<0.05
FREE CYANIDE	-	-	<0.5	-	<0.5	-	<0.05
PHENOL	-	-	44	-	32	-	38
SULFIDE as S	-	-	46	-	92	-	69
SULFITE as SO3	-	-	24	-	20	-	22
SULFATE as SO4	-	-	<5	-	<5	-	<5
THIOCYANATE	-	-	7.2	-	5	-	6.1
COD as O2	-	-	12600	-	13900	-	13250
TOC as C	-	-	23300	-	24000	-	23600

a All results as mg/L unless indicated in parentheses beside the component.

b - Means not analyzed

TABLE B-13. STEAM STRIPPER OPERATING CONDITIONS FOR RUN OF 11/02/84[a]

Flow Rates:	
Influent, m^3/h	0.0045 ± 0.0001
Steam, kg/h_3	2.08 ± 0.19
Effluent, m^3/h	0.0048 ± 0.0005
Overhead Condensate, m^3/h	0.00167
Overhead Vapor, L/h	-
Steam/Influent Ratio, kg/m^3:	459 ± 49
System Temperaturesm °C:	
Preheated Influent	89.7 ± 0.7
Stripper Overhead Vapor	100.5 ± 1.8
Stripper Packing Sections (top to bottom)	101.3 ± 1.5
	102.1 ± 1.0
	102.1 ± 1.0
	102.3 ± 0.9
Stripper Bottoms	80.6 ± 0.9
Packing Height, m:	1.2

[a]Values shown are mean ± sample standard deviation.

TABLE B-14. PERFORMANCE CHARACTERIZATION OF STEAM STRIPPER INFLUENT
STEAM/INFLUENT RATIO = 459 kg/m^3 AT 1.2 M PACKING HEIGHT 11/02/84

COMPONENT	SAMPLING TIME OF DAY (hrs) 0900	1100	1200	1300	1500	1600	1700	MEAN
pH (pH units)	9.13	9.13	9.25	9.14	9.14	9.26	9.13	9.17
CONDUCTIVITY (umhos/cm at 25 C)	38000	40000	41300	39000	39500	39400	39000	39600 +/- 800
AMMONIA as N	12300	12700	11500	12300	12600	11700	12400	12200 +/- 450
TOTAL ALKALINITY as CaCO3	-	-	37700	-	-	37300	-	37500
TOTAL CYANIDE	-	-	66	-	-	53	-	60
FREE CYANIDE	-	-	1.3	-	-	1.2	-	1.2
PHENOL	-	-	13	-	-	12	-	12
SULFIDE as S	-	-	120	-	-	170	-	145
SULFITE as SO3	-	-	110	-	-	120	-	115
SULFATE as SO4	-	-	<25	-	-	<25	-	<25
THIOCYANATE	-	-	680	-	-	740	-	710
COD as O2	-	-	18800	-	-	16800	-	17800
TOC as C	-	-	6190	-	-	5830	-	6010

a All results as mg/L unless indicated otherwise in parentheses beside the component.

b - Means not analyzed

TABLE B-15. PERFORMANCE CHARACTERIZATION OF STEAM STRIPPER EFFLUENT
STEAM/INFLUENT RATIO = 459 kg/m^3 AT 1.2 M PACKING HEIGHT 11/02/84

COMPONENT	SAMPLING TIME OF DAY (hrs) 0900	1100	1200	1300	1500	1600	1700	MEAN
pH (pH units)	8.26	7.05	6.63	6.68	6.75	7.08	6.79	7.02
CONDUCTIVITY (umhos/cm at 25 C)	2870	3810	4590	3480	4240	4710	4240	4010 +/-650
AMMONIA as N	400	590	600	610	610	650	600	580 +/-80
TOTAL ALKALINITY as CaCO3	-	-	340	-	-	350	-	345
TOTAL CYANIDE	-	-	56	-	-	30	-	43
FREE CYANIDE	-	-	2.0	-	-	3.3	-	2.7
PHENOL	-	-	12	-	-	8	-	10
SULFIDE as S	-	-	26	-	-	48	-	37
SULFITE as SO3	-	-	120	-	-	120	-	120
SULFATE as SO4	-	-	<25	-	-	<25	-	<25
THIOCYANATE	-	-	580	-	-	620	-	590
COD as O2	-	-	2670	-	-	2870	-	2720
TOC as C	-	-	830	-	-	930	-	880

a All results as mg/L unless indicated in parentheses beside the component.

b - Means not analyzed

TABLE B-16. PERFORMANCE CHARACTERIZATION OF STEAM STRIPPER CONDENSATE
STEAM/INFLUENT RATIO = 459 kg/m^3 AT 1.2 M PACKING HEIGHT 11/02/84

COMPONENT	SAMPLING TIME OF DAY (hrs) 1100	1200	1300	1500	1600	MEAN
pH [pH units]	9.26	9.45	9.76	9.74	9.65	9.57
CONDUCTIVITY [umhos/cm at 25 C]	116300	105800	192000	112800	114900	128300 +/-35800
AMMONIA as N	32400	25500	53600	30800	33800	35200 +/-10700
TOTAL ALKALINITY as CaCO3	-	97500	-	-	120000	108800
TOTAL CYANIDE	-	<0.5	-	-	<0.5	<0.05
FREE CYANIDE	-	<0.5	-	-	<0.5	<0.05
PHENOL	-	31	-	-	35	33
SULFIDE as S	-	56	-	-	130	95
SULFITE as SO3	-	26	-	-	20	23
SULFATE as SO4	-	<5	-	-	<5	<0.05
THIOCYANATE	-	1.7	-	-	2.8	2.2
COD as O2	-	18600	-	-	19700	19200
TOC as C	-	10500	-	-	12800	11600

a All results as mg/L unless indicated in parentheses beside the component.

b - Means not analyzed

TABLE B-17. STEAM STRIPPER OPERATING CONDITIONS FOR RUN OF 11/05/84[a]

Flow Rates:	
Influent, m^3/h	0.0070 ± 0.0002 m^3/h
Steam, kg/h	2.08 ± 0.19 kg/h
Effluent, m^3/h	0.0063 ± 0.0011 m^3/h
Overhead Condensate, m^3/h	0.0014 m^3/h
Overhead Vapor, L/h	-
Steam/Influent Ratio, kg/m^3:	297 ± 34
System Temperatures, °C:	
Preheated Influent	89.6 ± 1.4
Stripper Overhead Vapor	103.3 ± 0.7
Stripper Packing Sections (top to bottom)	102.7 ± 0.9
	102.9 ± 0.9
	102.7 ± 0.9
	102.8 ± 0.8
Stripper Bottoms	87.0 ± 0.6
Packing Height, m:	1.2

[a]Values shown are mean ± sample standard deviation.

TABLE B-18. PERFORMANCE CHARACTERIZATION OF STEAM STRIPPER INFLUENT
STEAM/INFLUENT RATIO = 297 kg/m^3 AT 1.2 M PACKING HEIGHT 11/05/84

COMPONENT	SAMPLING TIME OF DAY (hrs) 0930	1130	1230	1330	1530	1630	MEAN
pH (pH units)	-	8.49	8.46	8.46	8.38	8.46	8.45
CONDUCTIVITY (umhos/cm at 25 C)	5000	4750	5310	5000	5050	5360	5080 +/-330
AMMONIA as N	1500	860	740	800	770	700	890 +/-300
TOTAL ALKALINITY as CaCO3	-	-	940	-	-	830	880
TOTAL CYANIDE	-	-	45	-	-	50	48
FREE CYANIDE	-	-	2.8	-	-	2.6	2.7
PHENOL	-	-	26	-	-	28	27
SULFIDE as S	-	-	10	-	-	36	23
SULFITE as SO3	-	-	5	-	-	5	5
SULFATE as SO4	-	-	<25	-	-	<25	<25
THIOCYANATE	-	-	530	-	-	550	540
COD as O2	-	-	2680	-	-	2900	2490
TOC as O2	-	-	830	-	-	850	840

a All results as mg/L unless indicated in parentheses beside the component.

b - Means not analyzed

TABLE B-19. PERFORMANCE CHARACTERIZATION OF STEAM STRIPPER EFFLUENT
STEAM/INFLUENT RATIO = 297 kg/m^3 AT 1.2 M PACKING HEIGHT 11/05/84

COMPONENT	SAMPLING TIME OF DAY (hrs) 0830	1130	1230	1330	1530	1630	
pH [pH units]	7.05	7.00	7.05	6.87	6.83	7.09	6.98
CONDUCTIVITY [umhos/cm at 25 C]	3100	3890	4000	3760	3780	3940	3740 +/-330
AMMONIA as N	400	660	510	595	595	520	550 +/-90
TOTAL ALKALINITY as CaCO3	-	-	170	-	-	180	175
TOTAL CYANIDE	-	-	40	-	-	40	40
FREE CYANIDE	-	-	0.66	-	-	0.77	0.72
PHENOL	-	-	16	-	-	16	16
SULFIDE as S	-	-	14	-	-	15	14
SULFITE as SO3	-	-		-	-		
SULFATE as SO4	-	-	<25	-	-	<25	<25
THIOCYANATE	-	-	480	-	-	500	490
COD as O2	-	-	2440	-	-	2600	2520
TOC as C	-	-	710	-	-	750	730

a All results as mg/L unless indicated in parentheses beside the component.

b - Means not analyzed

TABLE B-20. PERFORMANCE CHARACTERIZATION OF STEAM STRIPPER CONDENSATE
STEAM/INFLUENT RATIO = 297 kg/m^3 AT 1.2 M PACKING HEIGHT 11/05/84

COMPONENT	SAMPLING TIME OF DAY						
	1000	1130	1230	1400	1530	1730	MEAN
pH [pH units]	8.99	8.98	9.28	9.34	9.28	9.37	9.21
CONDUCTIVITY [umhos/cm at 25 C]	6160	5200	5310	5610	5420	5310	5500 +/-350
AMMONIA as N	1620	1250	1590	1650	1640	1720	1580 +/-170
TOTAL ALKALINITY as CaCO3	-	-	5430	-	-	5480	5460
TOTAL CYANIDE	-	-	5.1	-	-	5.4	5.2
FREE CYANIDE	-	-	5.1	-	-	4.9	5
PHENOL	-	-	61	-	-	61	61
SULFIDE as S	-	-	15	-	-	18	16
SULFITE as SO3	-	-	1.5	-	-	1.5	1.5
SULFATE as SO4	-	-	<5	-	-	<25	<25
THIOCYANATE	-	-	<1	-	-	<1	<1
COD as O2	-	-	1270	-	-	1550	1410
TOC as C	-	-	700	-	-	710	705

a All results as mg/L unless indicated in parenthesis beside the component.

b - Means not analyzed

APPENDIX C

BENCH-SCALE STEAM STRIPPING

ENVIRONMENTAL CHARACTERIZATION DATA TABLES

TABLE C-1. WATER QUALITY ANALYSIS OF COMPOSITE SAMPLES 11-01-84

COMPONENT	INFLUENT	EFFLUENT	CONDENSATE
pH (pH units)	9.34	7.21	9.51
CONDUCTIVITY (umhos/cm at 25 C)	40900	5170	204000
CARBONATE ALKALINITY as CaCO3	17400	0	123800
BICARBONATE ALKALINITY as CaCO3	23400	360	88300
AMMONIA as N	12000	680	59800
FLUORIDE	55	61	<1
CHLORIDE	860	810	180
NITRATE as N	<1	<1	<1
NITRITE as N	<0.02	<0.02	<0.02
TOTAL DISSOLVED SOLIDS	1220	1340	280
TOTAL VOLATILE DISSOLVED SOLIDS	1000	950	280

a All results as mg/L unless indicated in parentheses beside the component.

TABLE C-2. WATER QUALITY ANALYSIS OF COMPOSITE SAMPLES 11-02-84

COMPONENT	INFLUENT	EFFLUENT	CONDENSATE
pH [pH units]	9.24	695	9.35
CONDUCTIVITY [umhos/cm at 25 C]	40200	4710	255000
CARBONATE ALKALINITY as CaCO3	27400	0	84300
BICARBONATE ALKALINITY as CaCO3	13700	500	40900
AMMONIA as N	12500	600	36200
FLUORIDE	64	57	<0.1
CHLORIDE	810	820	150
NITRATE as N	<1	<1	<1
NITRITE as N	<0.02	<0.02	<0.02
TOTAL DISSOLVED SOLIDS	1490	1310	290
TOTAL VOLATILE DISSOLVED SOLIDS	1230	970	280

a All results as mg/L unless indicated in parentheses beside the component.

TABLE C-3. WATER QUALITY ANALYSIS OF COMPOSITE SAMPLES 11-05-84

COMPONENT	INFLUENT	EFFLUENT	CONDENSATE
pH (pH units)	8.3	6.58	9.21
CONDUCTIVITY (umhos/cm at 25 C)	5510	3980	5790
CARBONATE ALKALINITY as CaCO3	0	0	1840
BICARBONATE ALKALINITY as CaCO3	1020	260	2580
AMMONIA as N	780	680	5800
FLUORIDE	56	56	0.15
CHLORIDE	810	810	145
NITRATE as N	<1	<1	<1
NITRITE as N	<0.02	<0.02	<0.02
TOTAL DISSOLVED SOLIDS	1510	1320	200
TOTAL VOLATILE DISSOLVED SOLIDS	1180	870	200

a All results as mg/L unless indicated in parentheses beside the component.

TABLE C-4. STEAM/INFLUENT RATIO = 282 KG/M^3 AT 1.2 M PACKING 11/1/84[a]

	Influent	Effluent	Condensate	Detection Limit
Ag	ND[b]	ND	ND	0.002
Al	ND	3.3	ND	0.05
As	2.7	0.33	1.2	0.06
B	23	28	ND	0.01
Ba	ND	0.028	ND	0.001
Be	0.001[c]	0.002[c]	ND	0.001
Ca	2.0	2.5	0.80	0.05
Cd	ND	0.054	ND	0.002
Co	ND	ND	ND	0.006
Cr	ND	0.056	ND	0.001
Cu	ND	0.056	ND	0.001
Fe	37	28	0.071	0.008
Hg	ND	ND	ND	0.03
K	9.6	9	7	0.04
Mg	ND	1.4	ND	0.03
Mn	ND	0.002[c]	ND	0.001
Mo	0.067	ND	0.009[c]	0.002
Na	0.66	4.1	ND	0.10
Ni	0.039	0.14	ND	0.003
P	4.4	8.4	6.7	0.18
Pb	ND	ND	ND	0.08
Sb	0.67	ND	0.28	0.03
Se	5.5	1.4	0.13[c]	0.08
Sr	0.078	0.016	0.06	0.001
Ti	ND	0.007[c]	ND	0.005
Tl	1.0	ND	0.74	0.09
V	ND	0.013[c]	ND	0.003
Zn	0.15	0.13	0.21	0.003

[a] Values expressed as μg/mL (ppm).
[b] ND = Not detected.
[c] Indicates value <5 times the detection limit.

TABLE C-5. STEAM/INFLUENT RATIO = 459 KG/M^3 AT 1.2 M PACKING 11/2/84[a]

	Influent	Effluent	Condensate	Detection Limit
Ag	ND[b]	ND	ND	0.002
Al	ND	4.9	ND	0.05
As	2.6	0.21[c]	1.8	0.06
B	23	25	ND	0.01
Ba	ND	0.022	ND	0.001
Be	ND	0.002[c]	ND	0.001
Ca	1.8	2.9	0.80	0.05
Cd	ND	0.086	ND	0.002
Co	ND	ND	ND	0.006
Cr	ND	0.044	ND	0.001
Cu	ND	0.056	ND	0.001
Fe	41	29	ND	0.008
Hg	ND	ND	ND	0.03
K	9	9	7	0.04
Mg	ND	1.6	ND	0.03
Mn	ND	0.010	ND	0.001
Mo	ND	ND	0.021	0.002
Na	ND	3.1	ND	0.10
Ni	0.028	0.14	ND	0.003
P	8.4	10	7.8	0.18
Pb	ND	ND	ND	0.08
Sb	0.02	ND	0.57	0.03
Se	5.6	1.6	0.44	0.08
Sr	0.078	0.017	0.098	0.001
Ti	ND	0.006*	ND	0.005
Tl	0.96	ND	0.96	0.09
V	ND	ND	ND	0.003
Zn	0.19	0.19	0.12	0.003

[a]Values expressed as µg/mL (ppm).
[b]ND = Not detected.
[c]Indicates value <5 times the detection limit.

TABLE C-6. STEAM/INFLUENT RATIO = 297 KG/M^3 AT 1.2 M PACKING HEIGHT 11/5/84[a]

	Influent	Effluent	Condensate	Detection Limit
Ag	ND[b]	ND	ND	0.002
Al	3.0	6.5	ND	0.05
As	0.18[c]	0.31	ND	0.06
B	26	23	ND	0.01
Ba	0.062	0.041	ND	0.001
Be	0.001[c]	0.001[c]	ND	0.001
Ca	7.7	8.6	ND	0.05
Cd	0.19	0.41	ND	0.002
Co	ND	ND	ND	0.006
Cr	0.046	0.046	ND	0.001
Cu	0.61	1.9	ND	0.001
Fe	22	18	ND	0.008
Hg	ND	ND	ND	0.03
K	6	6	ND	0.04
Mg	1.2	2.4	ND	0.03
Mn	0.27	0.034	ND	0.001
Mo	ND	ND	ND	0.002
Na	4.5	4.1	ND	0.10
Ni	0.11	0.074	ND	0.003
P	9.7	10	ND	0.18
Pb	ND	ND	ND	0.08
Sb	ND	ND	ND	0.03
Se	0.39[c]	0.34[c]	ND	0.08
Sr	0.041	0.043	ND	0.001
Ti	ND	ND	ND	0.005
Tl	ND	ND	ND	0.09
V	ND	0.004[c]	ND	0.003
Zn	0.28	0.25	0.017	0.003

[a] Values expressed as µg/mL (ppm).
[b] ND = Not detected.
[c] Indicates value <5 times the detection limit.

TABLE C-7. ELEMENTAL ANALYSIS OF LIME USED FOR WASTEWATER pH ADJUSTMENT (a)

Element	Concentration	Detection Limit
Ag	ND (b)	4.5
Al	1760	
As	ND	13
B	77	
Ba	6.6	
Be	ND	0.2
Ca	421,000	
Cd	1.0 (c)	
Co	ND	1.4
Cr	14	
Cu	290	
Fe	350	
K	424	
Mg	1620	
Mn	15	
Mo	5.5	
Na	240	
Ni	2.8 (c)	
Pb	ND	18
Sb	64	
Se	ND	18
Si	1940	
Tl	ND	20
V	14	
Zn	37	

a Values expressed as ug/g (ppm)
b ND = Not detected
c Indicates value <5 times the detection limit

aqualab inc.
9909 burnet road
austin, texas 78758
512/835-4980

6 December 1984

Ms. Barbara Hayes
RADIAN CORPORATION
P.O. Box 9948
850 Mo-Pac Blvd.
Austin TX 78766

Dear Ms. Hayes:

Enclosed are the analytical results for the samples received by AQUALAB on 9 November 1984. These samples were from your USEPA Project 68-02-3137 Task 56. Analyses, per your instructions, included base/neutral and acid priority pollutants, cresols and xylenols.

The methods used for these analyses are found in "Methods for Organic Chemical Analysis of Municipal and Industrial Wastewater", EPA-600/4-82-057 July 1982.

> Base/Neutral and Acid (BN/A) compounds were analyzed using EPA Method 625. Aliquots of the samples are extracted first at basic and then acidic ph's with methylene chloride. The extracts are concentrated and analyzed by GC/MS.

Due to the high alkalinity of certain samples, a large amount of acid was required to lower the pH during the acid extraction. This pH adjustment was highly exothermic, therefore, the samples were cooled by ice and only a small amount of acid was added at a time.

Total cresol results are based on the response of phenol. Xylenol (dimethylphenol) exists as six isomers. The 2,4 isomer is a priority pollutant and is reported separately, except for sample W84-128 where separation of the isomers was not possible. Xylenol results are based on the response of 2,4-dimethylphenol.

Because of the complexity of these samples, extra time was needed to obtain quality results. I am sorry for this delay in providing these results. If after reviewing these results you have any questions, please feel free to call. AQUALAB has been pleased to provide these analytical services for you.

Sincerely,

AQUALAB INC.

Pamela S. Jupe
Division Manager

PSJ/hn

aqualab inc.
9909 burnet road
austin, texas 78758
512 835-4980

30 Nov. 1984

analytical report sample no. 15266

Ms. Barbara Hayes
RADIAN CORPORATION
P.O. Box 9948 - 8501 Mo-Pac Blvd.
Austin TX 78766

SAMPLE DESCRIPTION: W84-126

BASE/NEUTRAL COMPOUNDS

ug/L	Compound	ug/L	Compound
<100	Acenaphthene (1B)	<100	Nitrobenzene (56B)
<500	Benzidine (5B)	<100	N-Nitrosodimethylamine (61B)
<100	1,2,4-Trichlorobenzene (8B)	<100	N-Nitrosodiphenylamine (62B)
<100	Hexachlorobenzene (9B)	<100	N-Nitrosodi-n-propylamine (63B)
<100	Hexachloroethane (12B)	<100	Bis(2-Ethylhexyl)Phthalate (66B)
<100	Bis(2-chloroethyl)Ether (18B)	<100	Butyl Benzyl Phthalate (67B)
<100	2-Chloronaphthalene (20B)	<100	Di-N-Butyl Phthalate (68B)
<100	1,2-Dichlorobenzene (25B)	<100	Di-N-Octyl Phthalate (69B)
<100	1,3-Dichlorobenzene (26B)	<100	Diethyl Phthalate (70B)
<100	1,4-Dichlorobenzene (27B)	<100	Dimethyl Phthalate (71B)
<250	3,3'-Dichlorobenzidine (28B)	<100	Benzo(a)Anthracene (72B)
<100	2,4-Dinitrotoluene (35B)	<100	Benzo(a)Pyrene (73B)
<100	2,6-Dinitrotoluene (36B)	<100	Benzo(b)Fluoranthene (74B)
<100	1,2-Diphenylhydrazine (37B)	<100	Benzo(k)Fluoranthene (75B)
<100	Fluoranthene (39B)	<100	Chrysene (76B)
<100	4-Chlorophenyl Phenyl Ether (40)	<100	Acenaphthylene (77B)
<100	4-Bromophenyl Phenyl Ether (41B)	<100	Anthracene (78B)
<100	Bis(2-Chloroisopropyl)Ether (42)	<100	Benzo(ghi)Perylene (79B)
<100	Bis(2-Chloroethoxy)Methane (43B)	<100	Fluorene (80B)
<100	Hexachlorobutadiene (52B)	<100	Phenanthrene (81B)
<250	Hexachlorocyclopentadiene (53B)	<100	Dibenzo(a,h)Anthracene (82B)
<100	Isophorone (54B)	<100	Ideno(1,2,3-cd)Pyrene (83B)
<100	Naphthalene (55B)	<100	Pyrene (84B)

ACID COMPOUNDS

<100	2,4,6-Trichlorophenol (21A)	<100	4-Nitrophenol (58A)
<100	4-Chloro-3-Methylphenol (22A)	<250	2,4-Dinitrophenol (59A)
<100	2-Chlorophenol (24A)	<250	2-Methyl-4,6-dinitrophenol (60A)
<100	2,4-Dichlorophenol (31A)	<100	Pentachlorophenol (64A)
677	2,4-Dimethylphenol (34A)	2660	Phenol (65A)
<100	2-Nitrophenol (57A)	2720	Cresols, total
1080	Xylenols (other than 2,4 isomer)		

Cresols based on response of phenol.
Xylenols based on response of 2,4-dimethylphenol.

Pam Jupe

A 103

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9909 burnet road
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512/835-4980

30 Nov. 1984

analytical report

sample no. 15267

Ms. Barbara Hayes
RADIAN CORPORATION
P.O. Box 9948 - 8501 Mo-Pac Blvd.
Austin TX 78766

SAMPLE DESCRIPTION: W84-127

BASE/NEUTRAL COMPOUNDS

ug/L	Compound
<100	Acenaphthene (1B)
<500	Benzidine (5B)
<100	1,2,4-Trichlorobenzene (8B)
<100	Hexachlorobenzene (9B)
<100	Hexachloroethane (12B)
<100	Bis(2-chloroethyl)Ether (18B)
<100	2-Chloronaphthalene (20B)
<100	1,2-Dichlorobenzene (25B)
<100	1,3-Dichlorobenzene (26B)
<100	1,4-Dichlorobenzene (27B)
<250	3,3'-Dichlorobenzidine (28B)
<100	2,4-Dinitrotoluene (35B)
<100	2,6-Dinitrotoluene (36B)
<100	1,2-Diphenylhydrazine (37B)
<100	Fluoranthene (39B)
<100	4-Chlorophenyl Phenyl Ether (40)
<100	4-Bromophenyl Phenyl Ether (41B)
<100	Bis(2-Chloroisopropyl)Ether (42)
<100	Bis(2-Chloroethoxy)Methane (43B)
<100	Hexachlorobutadiene (52B)
<250	Hexachlorocyclopentadiene (53B)
<100	Isophorone (54B)
<100	Naphthalene (55B)

ug/L	Compound
<100	Nitrobenzene (56B)
<100	N-Nitrosodimethylamine (61B)
<100	N-Nitrosodiphenylamine (62B)
<100	N-Nitrosodi-n-propylamine (63B)
<100	Bis(2-Ethylhexyl)Phthalate (66B)
<100	Butyl Benzyl Phthalate (67B)
<100	Di-N-Butyl Phthalate (68B)
<100	Di-N-Octyl Phthalate (69B)
<100	Diethyl Phthalate (70B)
<100	Dimethyl Phthalate (71B)
<100	Benzo(a)Anthracene (72B)
<100	Benzo(a)Pyrene (73B)
<100	Benzo(b)Fluoranthene (74B)
<100	Benzo(k)Fluoranthene (75B)
<100	Chrysene (76B)
<100	Acenaphthylene (77B)
<100	Anthracene (78B)
<100	Benzo(ghi)Perylene (79B)
<100	Fluorene (80B)
<100	Phenanthrene (81B)
<100	Dibenzo(a,h)Anthracene (82B)
<100	Ideno(1,2,3-cd)Pyrene (83B)
<100	Pyrene (84B)

ACID COMPOUNDS

ug/L	Compound
<100	2,4,6-Trichlorophenol (21A)
<100	4-Chloro-3-Methylphenol (22A)
<100	2-Chlorophenol (24A)
<100	2,4-Dichlorophenol (31A)
<100	2,4-Dimethylphenol (34A)
<100	2-Nitrophenol (57A)
556	Xylenols (other than 2,4 isomer)

ug/L	Compound
<100	4-Nitrophenol (58A)
<250	2,4-Dinitrophenol (59A)
<250	2-Methyl-4,6-dinitrophenol (60A)
<100	Pentachlorophenol (64A)
4850	Phenol (65A)
2720	Cresols, total

Cresols based on response of phenol.
Xylenols based on response of 2,4-dimethylphenol.

Pam Jupe

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30 Nov. 1984

analytical report

sample no. 15268

Ms. Barbara Hayes
RADIAN CORPORATION
P.O. Box 9948 - 8501 Mo-Pac Blvd.
Austin TX 78766

SAMPLE DESCRIPTION: W84-128

BASE/NEUTRAL COMPOUNDS

ug/L	Compound	ug/L	Compound
<10	Acenaphthene (1B)	<10	Nitrobenzene (56B)
<50	Benzidine (5B)	<10	N-Nitrosodimethylamine (61B)
<10	1,2,4-Trichlorobenzene (8B)	<10	N-Nitrosodiphenylamine (62B)
<10	Hexachlorobenzene (9B)	<10	N-Nitrosodi-n-propylamine (63B)
<10	Hexachloroethane (12B)	<10	Bis(2-Ethylhexyl)Phthalate (66B)
<10	Bis(2-chloroethyl)Ether (18B)	<10	Butyl Benzyl Phthalate (67B)
<10	2-Chloronaphthalene (20B)	<10	Di-N-Butyl Phthalate (68B)
<10	1,2-Dichlorobenzene (25B)	<10	Di-N-Octyl Phthalate (69B)
<10	1,3-Dichlorobenzene (26B)	<10	Diethyl Phthalate (70B)
<10	1,4-Dichlorobenzene (27B)	<10	Dimethyl Phthalate (71B)
<25	3,3'-Dichlorobenzidine (28B)	<10	Benzo(a)Anthracene (72B)
<10	2,4-Dinitrotoluene (35B)	<10	Benzo(a)Pyrene (73B)
<10	2,6-Dinitrotoluene (36B)	<10	Benzo(b)Fluoranthene (74B)
<10	1,2-Diphenylhydrazine (37B)	<10	Benzo(k)Fluoranthene (75B)
<10	Fluoranthene (39B)	<10	Chrysene (76B)
<10	4-Chlorophenyl Phenyl Ether(40)	<10	Acenaphthylene (77B)
<10	4-Bromophenyl Phenyl Ether(41B)	<10	Anthracene (78B)
<10	Bis(2-Chloroisopropyl)Ether(42)	<10	Benzo(ghi)Perylene (79B)
<10	Bis(2-Chloroethoxy)Methane(43B)	<10	Fluorene (80B)
<10	Hexachlorobutadiene (52B)	<10	Phenanthrene (81B)
<25	Hexachlorocyclopentadiene (53B)	<10	Dibenzo(a,h)Anthracene (82B)
<10	Isophorone (54B)	<10	Ideno(1,2,3-cd)Pyrene (83B)
<10	Naphthalene (55B)	<10	Pyrene (84B)

ACID COMPOUNDS

<10	2,4,6-Trichlorophenol (21A)	<10	4-Nitrophenol (58A)
<10	4-Chloro-3-methylphenol (22A)	<25	2,4-Dinitrophenol (59A)
<10	2-Chlorophenol (24A)	<25	2-Methyl-4,6-dinitrophenol (60A)
<10	2,4-Dichlorophenol (31A)	17.9	Pentachlorophenol (64A)
2780*	2,4-Dimethylphenol (34A)	47300	Phenol (65A)
<10	2-Nitrophenol (57A)	16500	Cresols, total

Cresols based on response of phenol.
*Xylenol isomeric separation not possible due to high concentration.

Pam Jupe

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30 Nov. 1984

analytical report

sample no. 15269

Ms. Barbara Hayes
RADIAN CORPORATION
P.O. Box 9948 - 8501 Mo-Pac Blvd.
Austin TX 78766

SAMPLE DESCRIPTION: W84-150

BASE/NEUTRAL COMPOUNDS

ug/L	Compound	ug/L	Compound
<100	Acenaphthene (1B)	<100	Nitrobenzene (56B)
<500	Benzidine (5B)	<100	N-Nitrosodimethylamine (61B)
<100	1,2,4-Trichlorobenzene (8B)	<100	N-Nitrosodiphenylamine (62B)
<100	Hexachlorobenzene (9B)	<100	N-Nitrosodi-n-propylamine (63B)
<100	Hexachloroethane (12B)	<100	Bis(2-Ethylhexyl)Phthalate (66B)
<100	Bis(2-chloroethyl)Ether (18B)	<100	Butyl Benzyl Phthalate (67B)
<100	2-Chloronaphthalene (20B)	<100	Di-N-Butyl Phthalate (68B)
<100	1,2-Dichlorobenzene (25B)	<100	Di-N-Octyl Phthalate (69B)
<100	1,3-Dichlorobenzene (26B)	<100	Diethyl Phthalate (70B)
<100	1,4-Dichlorobenzene (27B)	<100	Dimethyl Phthalate (71B)
<250	3,3'-Dichlorobenzidine (28B)	<100	Benzo(a)Anthracene (72B)
<100	2,4-Dinitrotoluene (35B)	<100	Benzo(a)Pyrene (73B)
<100	2,6-Dinitrotoluene (36B)	<100	Benzo(b)Fluoranthene (74B)
<100	1,2-Diphenylhydrazine (37B)	<100	Benzo(k)Fluoranthene (75B)
<100	Fluoranthene (39B)	<100	Chrysene (76B)
<100	4-Chlorophenyl Phenyl Ether (40)	<100	Acenaphthylene (77B)
<100	4-Bromophenyl Phenyl Ether (41B)	<100	Anthracene (78B)
<100	Bis(2-Chloroisopropyl)Ether (42)	<100	Benzo(ghi)Perylene (79B)
<100	Bis(2-Chloroethoxy)Methane (43B)	<100	Fluorene (80B)
<100	Hexachlorobutadiene (52B)	<100	Phenanthrene (81B)
<250	Hexachlorocyclopentadiene (53B)	<100	Dibenzo(a,h)Anthracene (82B)
<100	Isophorone (54B)	<100	Ideno(1,2,3-cd)Pyrene (83B)
<100	Naphthalene (55B)	<100	Pyrene (84B)

ACID COMPOUNDS

<100	2,4,6-Trichlorophenol (21A)	<100	4-Nitrophenol (58A)
<100	4-Chloro-3-Methylphenol (22A)	<250	2,4-Dinitrophenol (59A)
<100	2-Chlorophenol (24A)	<250	2-Methyl-4,6-dinitrophenol (60A)
<100	2,4-Dichlorophenol (31A)	<100	Pentachlorophenol (64A)
1890	2,4-Dimethylphenol (34A)	8720	Phenol (65A)
<100	2-Nitrophenol (57A)	6330	Cresols, total
1390	Xylenols (other than 2,4 isomer)		

Cresols based on response of phenol.
Xylenols based on response of 2,4-dimethylphenol.

Pam Jupe

aqualab inc.
9909 burnet road
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512/835-4980

30 Nov. 1984

analytical report sample no. 15270

Ms. Barbara Hayes
RADIAN CORPORATION
P.O. Box 9948 - 8501 Mo-Pac Blvd.
Austin TX 78766

SAMPLE DESCRIPTION: W84-151

BASE/NEUTRAL COMPOUNDS

ug/L	Compound	ug/L	Compound
<100	Acenaphthene (1B)	<100	Nitrobenzene (56B)
<500	Benzidine (5B)	<100	N-Nitrosodimethylamine (61B)
<100	1,2,4-Trichlorobenzene (8B)	<100	N-Nitrosodiphenylamine (62B)
<100	Hexachlorobenzene (9B)	<100	N-Nitrosodi-n-propylamine (63B)
<100	Hexachloroethane (12B)	<100	Bis(2-Ethylhexyl)Phthalate (66B)
<100	Bis(2-chloroethyl)Ether (18B)	<100	Butyl Benzyl Phthalate (67B)
<100	2-Chloronaphthalene (20B)	<100	Di-N-Butyl Phthalate (68B)
<100	1,2-Dichlorobenzene (25B)	<100	Di-N-Octyl Phthalate (69B)
<100	1,3-Dichlorobenzene (26B)	<100	Diethyl Phthalate (70B)
<100	1,4-Dichlorobenzene (27B)	<100	Dimethyl Phthalate (71B)
<250	3,3'-Dichlorobenzidine (28B)	<100	Benzo(a)Anthracene (72B)
<100	2,4-Dinitrotoluene (35B)	<100	Benzo(a)Pyrene (73B)
<100	2,6-Dinitrotoluene (36B)	<100	Benzo(b)Fluoranthene (74B)
<100	1,2-Diphenylhydrazine (37B)	<100	Benzo(k)Fluoranthene (75B)
<100	Fluoranthene (39B)	<100	Chrysene (76B)
<100	4-Chlorophenyl Phenyl Ether (40)	<100	Acenaphthylene (77B)
<100	4-Bromophenyl Phenyl Ether (41B)	<100	Anthracene (78B)
<100	Bis(2-Chloroisopropyl)Ether (42)	<100	Benzo(ghi)Perylene (79B)
<100	Bis(2-Chloroethoxy)Methane (43B)	<100	Fluorene (80B)
<100	Hexachlorobutadiene (52B)	<100	Phenanthrene (81B)
<250	Hexachlorocyclopentadiene (53B)	<100	Dibenzo(a,h)Anthracene (82B)
<100	Isophorone (54B)	<100	Ideno(1,2,3-cd)Pyrene (83B)
<100	Naphthalene (55B)	<100	Pyrene (84B)

ACID COMPOUNDS

<100	2,4,6-Trichlorophenol (21A)	<100	4-Nitrophenol (58A)
<100	4-Chloro-3-Methylphenol (22A)	<250	2,4-Dinitrophenol (59A)
<100	2-Chlorophenol (24A)	<250	2-Methyl-4,6-dinitrophenol (60A)
<100	2,4-Dichlorophenol (31A)	<100	Pentachlorophenol (64A)
302	2,4-Dimethylphenol (34A)	4960	Phenol (65A)
<100	2-Nitrophenol (57A)	2320	Cresols, total
103	Xylenols (other than 2,4 isomer)		

Cresols based on response of phenol.
Xylenols based on response of 2,4-dimethylphenol.

Pam Jupe

Pam Jupe

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512/835-4980

30 Nov. 1984

analytical report

sample no. 15271

Ms. Barbara Hayes
RADIAN CORPORATION
P.O. Box 9948 - 8501 Mo-Pac Blvd.
Austin TX 78766

SAMPLE DESCRIPTION: W84-152

BASE/NEUTRAL COMPOUNDS

ug/L	Compound	ug/L	Compound
<10	Acenaphthene (1B)	<10	Nitrobenzene (56B)
<50	Benzidine (5B)	<10	N-Nitrosodimethylamine (61B)
<10	1,2,4-Trichlorobenzene (8B)	<10	N-Nitrosodiphenylamine (62B)
<10	Hexachlorobenzene (9B)	<10	N-Nitrosodi-n-propylamine (63B)
<10	Hexachloroethane (12B)	<10	Bis(2-Ethylhexyl)Phthalate (66B)
<10	Bis(2-chloroethyl)Ether (18B)	<10	Butyl Benzyl Phthalate (67B)
<10	2-Chloronaphthalene (20B)	<10	Di-N-Butyl Phthalate (68B)
<10	1,2-Dichlorobenzene (25B)	<10	Di-N-Octyl Phthalate (69B)
<10	1,3-Dichlorobenzene (26B)	<10	Diethyl Phthalate (70B)
<10	1,4-Dichlorobenzene (27B)	<10	Dimethyl Phthalate (71B)
<25	3,3'-Dichlorobenzidine (28B)	<10	Benzo(a)Anthracene (72B)
<10	2,4-Dinitrotoluene (35B)	<10	Benzo(a)Pyrene (73B)
<10	2,6-Dinitrotoluene (36B)	<10	Benzo(b)Fluoranthene (74B)
<10	1,2-Diphenylhydrazine (37B)	<10	Benzo(k)Fluoranthene (75B)
<10	Fluoranthene (39B)	<10	Chrysene (76B)
<10	4-Chlorophenyl Phenyl Ether(40)	<10	Acenaphthylene (77B)
<10	4-Bromophenyl Phenyl Ether(41B)	<10	Anthracene (78B)
<10	Bis(2-Chloroisopropyl)Ether(42)	<10	Benzo(ghi)Perylene (79B)
<10	Bis(2-Chloroethoxy)Methane(43B)	<10	Fluorene (80B)
<10	Hexachlorobutadiene (52B)	<10	Phenanthrene (81B)
<25	Hexachlorocyclopentadiene (53B)	<10	Dibenzo(a,h)Anthracene (82B)
<10	Isophorone (54B)	<10	Ideno(1,2,3-cd)Pyrene (83B)
<10	Naphthalene (55B)	<10	Pyrene (84B)

ACID COMPOUNDS

<10	2,4,6-Trichlorophenol (21A)	<10	4-Nitrophenol (58A)
<10	4-Chloro-3-methylphenol (22A)	<25	2,4-Dinitrophenol (59A)
<10	2-Chlorophenol (24A)	<25	2-Methyl-4,6-dinitrophenol (60A)
<10	2,4-Dichlorophenol (31A)	<10	Pentachlorophenol (64A)
1240	2,4-Dimethylphenol (34A)	23200	Phenol (65A)
<10	2-Nitrophenol (57A)	13000	Cresols, total
1290	Xylenols (othr than 2,4 isomer)		

Cresols based on response of phenol.
Xylenols based on response of 2,4-dimethylphenol.

Pam Jupe

aqualab inc.
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30 Nov. 1984

analytical report sample no. 15272

Ms. Barbara Hayes
RADIAN CORPORATION
P.O. Box 9948 - 8501 Mo-Pac Blvd.
Austin TX 78766

SAMPLE DESCRIPTION: W84-171

BASE/NEUTRAL COMPOUNDS

ug/L	Compound	ug/L	Compound
<100	Acenaphthene (1B)	<100	Nitrobenzene (56B)
<500	Benzidine (5B)	<100	N-Nitrosodimethylamine (61B)
<100	1,2,4-Trichlorobenzene (8B)	<100	N-Nitrosodiphenylamine (62B)
<100	Hexachlorobenzene (9B)	<100	N-Nitrosodi-n-propylamine (63B)
<100	Hexachloroethane (12B)	<100	Bis(2-Ethylhexyl)Phthalate (66B)
<100	Bis(2-chloroethyl)Ether (18B)	<100	Butyl Benzyl Phthalate (67B)
<100	2-Chloronaphthalene (20B)	<100	Di-N-Butyl Phthalate (68B)
<100	1,2-Dichlorobenzene (25B)	<100	Di-N-Octyl Phthalate (69B)
<100	1,3-Dichlorobenzene (26B)	<100	Diethyl Phthalate (70B)
<100	1,4-Dichlorobenzene (27B)	<100	Dimethyl Phthalate (71B)
<250	3,3'-Dichlorobenzidine (28B)	<100	Benzo(a)Anthracene (72B)
<100	2,4-Dinitrotoluene (35B)	<100	Benzo(a)Pyrene (73B)
<100	2,6-Dinitrotoluene (36B)	<100	Benzo(b)Fluoranthene (74B)
<100	1,2-Diphenylhydrazine (37B)	<100	Benzo(k)Fluoranthene (75B)
<100	Fluoranthene (39B)	<100	Chrysene (76B)
<100	4-Chlorophenyl Phenyl Ether(40)	<100	Acenaphthylene (77B)
<100	4-Bromophenyl Phenyl Ether(41B)	<100	Anthracene (78B)
<100	Bis(2-Chloroisopropyl)Ether(42)	<100	Benzo(ghi)Perylene (79B)
<100	Bis(2-Chloroethoxy)Methane(43B)	<100	Fluorene (80B)
<100	Hexachlorobutadiene (52B)	<100	Phenanthrene (81B)
<250	Hexachlorocyclopentadiene (53B)	<100	Dibenzo(a,h)Anthracene (82B)
<100	Isophorone (54B)	<100	Ideno(1,2,3-cd)Pyrene (83B)
<100	Naphthalene (55B)	<100	Pyrene (84B)

ACID COMPOUNDS

<100	2,4,6-Trichlorophenol (21A)	<100	4-Nitrophenol (58A)
<100	4-Chloro-3-methylphenol (22A)	<250	2,4-Dinitrophenol (59A)
<100	2-Chlorophenol (24A)	<250	2-Methyl-4,6-dinitrophenol (60A)
<100	2,4-Dichlorophenol (31A)	<100	Pentachlorophenol (64A)
284	2,4-Dimethylphenol (34A)	18100	Phenol (65A)
<100	2-Nitrophenol (57A)	9160	Cresols, total
1170	Xylenols (other than 2,4 isomer)		

Cresols based on response of phenol.
Xylenols based on response of 2,4-dimethylphenol.

Pam Jupe

A-103

aqualab inc.
9909 burnet road
austin, texas 78758
512/835-4980

30 Nov. 1984

analytical report

sample no. 15273

Ms. Barbara Hayes
RADIAN CORPORATION
P.O. Box 9948 - 8501 Mo-Pac Blvd.
Austin TX 78766

SAMPLE DESCRIPTION: W84-172

BASE/NEUTRAL COMPOUNDS

ug/L	Compound	ug/L	Compound
<100	Acenaphthene (1B)	<100	Nitrobenzene (56B)
<500	Benzidine (5B)	<100	N-Nitrosodimethylamine (61B)
<100	1,2,4-Trichlorobenzene (8B)	<100	N-Nitrosodiphenylamine (62B)
<100	Hexachlorobenzene (9B)	<100	N-Nitrosodi-n-propylamine (63B)
<100	Hexachloroethane (12B)	<100	Bis(2-Ethylhexyl)Phthalate (66B)
<100	Bis(2-chloroethyl)Ether (18B)	<100	Butyl Benzyl Phthalate (67B)
<100	2-Chloronaphthalene (20B)	<100	Di-N-Butyl Phthalate (68B)
<100	1,2-Dichlorobenzene (25B)	<100	Di-N-Octyl Phthalate (69B)
<100	1,3-Dichlorobenzene (26B)	<100	Diethyl Phthalate (70B)
<100	1,4-Dichlorobenzene (27B)	<100	Dimethyl Phthalate (71B)
<250	3,3'-Dichlorobenzidine (28B)	<100	Benzo(a)Anthracene (72B)
<100	2,4-Dinitrotoluene (35B)	<100	Benzo(a)Pyrene (73B)
<100	2,6-Dinitrotoluene (36B)	<100	Benzo(b)Fluoranthene (74B)
<100	1,2-Diphenylhydrazine (37B)	<100	Benzo(k)Fluoranthene (75B)
<100	Fluoranthene (39B)	<100	Chrysene (76B)
<100	4-Chlorophenyl Phenyl Ether(40)	<100	Acenaphthylene (77B)
<100	4-Bromophenyl Phenyl Ether(41B)	<100	Anthracene (78B)
<100	Bis(2-Chloroisopropyl)Ether(42)	<100	Benzo(ghi)Perylene (79B)
<100	Bis(2-Chloroethoxy)Methane(43B)	<100	Fluorene (80B)
<100	Hexachlorobutadiene (52B)	<100	Phenanthrene (81B)
<250	Hexachlorocyclopentadiene (53B)	<100	Dibenzo(a,h)Anthracene (82B)
<100	Isophorone (54B)	<100	Ideno(1,2,3-cd)Pyrene (83B)
<100	Naphthalene (55B)	<100	Pyrene (84B)

ACID COMPOUNDS

<100	2,4,6-Trichlorophenol (21A)	<100	4-Nitrophenol (58A)
<100	4-Chloro-3-methylphenol (22A)	<250	2,4-Dinitrophenol (59A)
<100	2-Chlorophenol (24A)	<250	2-Methyl-4,6-dinitrophenol (60A)
<100	2,4-Dichlorophenol (31A)	<100	Pentachlorophenol (64A)
<100	2,4-Dimethylphenol (34A)	10600	Phenol (65A)
<100	2-Nitrophenol (57A)	4180	Cresols, total
<100	Xylenols (other than 2,4 isomer)		

Cresols based on response of phenol.
Xylenols based on response of 2,4-dimethylphenol.

Pam Jupe

aqualab inc.
9909 burnet road
austin, texas 78758
512/835-4980

30 Nov. 1984

analytical report

sample no. 15274

Ms. Barbara Hayes
RADIAN CORPORATION
P.O. Box 9948 - 8501 Mo-Pac Blvd.
Austin TX 78766

SAMPLE DESCRIPTION: W84-173

BASE/NEUTRAL COMPOUNDS

ug/L	Compound	ug/L	Compound
<10	Acenaphthene (1B)	<10	Nitrobenzene (56B)
<50	Benzidine (5B)	<10	N-Nitrosodimethylamine (61B)
<10	1,2,4-Trichlorobenzene (8B)	<10	N-Nitrosodiphenylamine (62B)
<10	Hexachlorobenzene (9B)	<10	N-Nitrosodi-n-propylamine (63B)
<10	Hexachloroethane (12B)	<10	Bis(2-Ethylhexyl)Phthalate (66B)
<10	Bis(2-chloroethyl)Ether (18B)	<10	Butyl Benzyl Phthalate (67B)
<10	2-Chloronaphthalene (20B)	<10	Di-N-Butyl Phthalate (68B)
<10	1,2-Dichlorobenzene (25B)	<10	Di-N-Octyl Phthalate (69B)
<10	1,3-Dichlorobenzene (26B)	<10	Diethyl Phthalate (70B)
<10	1,4-Dichlorobenzene (27B)	<10	Dimethyl Phthalate (71B)
<25	3,3'-Dichlorobenzidine (28B)	<10	Benzo(a)Anthracene (72B)
<10	2,4-Dinitrotoluene (35B)	<10	Benzo(a)Pyrene (73B)
<10	2,6-Dinitrotoluene (36B)	<10	Benzo(b)Fluoranthene (74B)
<10	1,2-Diphenylhydrazine (37B)	<10	Benzo(k)Fluoranthene (75B)
<10	Fluoranthene (39B)	<10	Chrysene (76B)
<10	4-Chlorophenyl Phenyl Ether(40)	<10	Acenaphthylene (77B)
<10	4-Bromophenyl Phenyl Ether(41B)	<10	Anthracene (78B)
<10	Bis(2-Chloroisopropyl)Ether(42)	<10	Benzo(ghi)Perylene (79B)
<10	Bis(2-Chloroethoxy)Methane(43B)	<10	Fluorene (80B)
<10	Hexachlorobutadiene (52B)	<10	Phenanthrene (81B)
<25	Hexachlorocyclopentadiene (53B)	<10	Dibenzo(a,h)Anthracene (82B)
<10	Isophorone (54B)	<10	Ideno(1,2,3-cd)Pyrene (83B)
<10	Naphthalene (55B)	<10	Pyrene (84B)

ACID COMPOUNDS

<10	2,4,6-Trichlorophenol (21A)	<10	4-Nitrophenol (58A)
<10	4-Chloro-3-methylphenol (22A)	<25	2,4-Dinitrophenol (59A)
<10	2-Chlorophenol (24A)	<25	2-Methyl-4,6-dinitrophenol (60A)
<10	2,4-Dichlorophenol (31A)	<10	Pentachlorophenol (64A)
190	2,4-Dimethylphenol (34A)	38000	Phenol (65A)
<10	2-Nitrophenol (57A)	28600	Cresols, total
468	Xylenols (othr than 2,4 isomer)		

Cresols based on response of phenol.
Xylenols based on response of 2,4-dimethylphenol.

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APPENDIX D

SAMPLE HANDLING/ANALYSIS PROCEDURES (INCLUDING ANALYTICAL QA/QC)

INTRODUCTION

Radian Corporation has included quality assurance (QA) and quality control (QC) as critical elements of all sampling and analysis contracts for a number of years. Because of the variety of activities in which Radian is involved, multiple QA/QC programs have been developed for the primary project areas of the corporation. The quality assurance and quality control procedures used in this program are based on proven techniques that have been adopted or developed by Radian and used throughout our sampling and analysis procedures. Radian's basic quality control program includes procedures for calibration, sample handling, equipment maintenance, reagent preparation, and quality control test samples. To these are added any additional client requirements such as spiking studies, additional linearity evaluations, and replicate analyses. Quality assurance begins with the preparation of the test plan and calibration of equipment and carries through the sampling and analysis to the reporting of data.

The following part, Sampling Handling and Analysis Techniques, briefly summarizes some of the practices used for sample handling and analysis and the data pertinent to this treatability study. The last part, Bulk Wastewater Sample, outlines the collection of the bulk wastewater samples and the analysis performed across the program period to assess the stability of the samples.

SAMPLE HANDLING AND ANALYSIS TECHNIQUES

The analytical methods which were used during the steam stripping study are listed in Table D-1. All analytical methods are recognized EPA or APHA, AWWA, or WPFC Standard Methods except for formate. Formate was determined by ion chromatography in accordance with the Dionex instrument manual and the method reported by Haynes. References for each of the procedures are given as footnotes to Table D-1.

During the stripping runs, grab samples of the stripper influent, effluent, and condensate were collected at one hour intervals for the analysis of pH, conductivity, and ammonia. Samples of these streams were also collected at two other time periods during each eight-hour test run for ten additional water quality parameters including: alkalinity, TOC, COD, total cyanide, free cyanide, thiocyanate, phenol, sulfide, sulfite, and sulfate. Samples for pH, conductivity, and ammonia were analyzed immediately after collection by the stripper operations personnel. All remaining samples were preserved and distributed to the appropriate analytical laboratories at the end of the test run.

Preservation procedures for the liquid samples followed those recommended by EPA in Methods for Chemical Analysis of Water and Wastes. These techniques and the recommended holding times are listed in Table D-2. In practice, a single sample was obtained and preserved for those parameters having the same preservation requirements. Figure D-1 outlines the preservation scheme used.

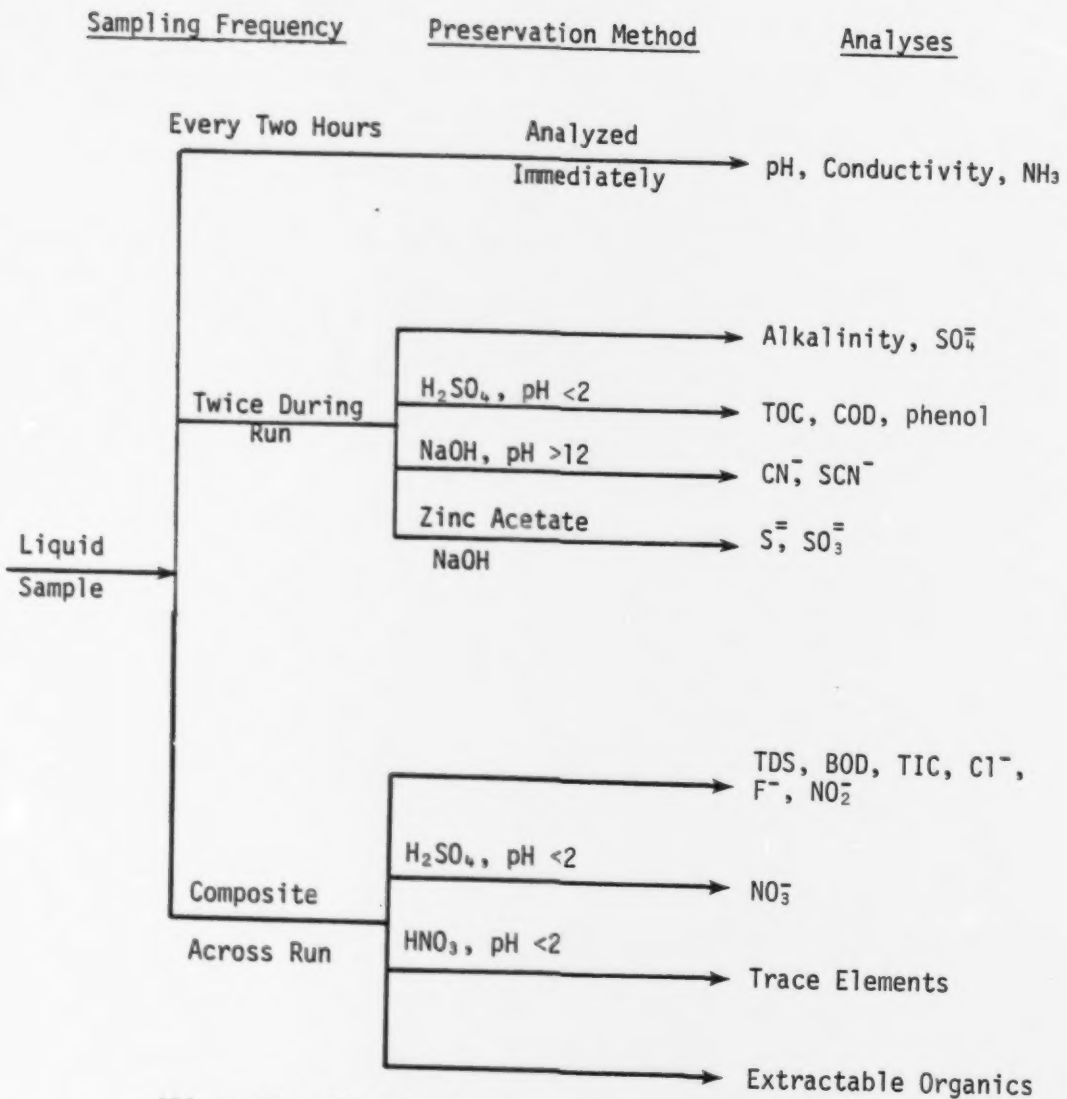
In addition to the performance evaluation samples, grab samples of the influent, effluent, and condensate were collected at two hour intervals and were composited to yield one sample at each stream for the run. Equal aliquots of the individually preserved grabs were combined to provide the composite samples for analysis.

During the study, about ten percent of the sample analysis were performed in duplicate or as replicate samples. A randomly selected sampling of the

TABLE D-1. WATER ANALYSIS METHODOLOGY

Parameter	Method	Reference[a]
pH	Electrometry	EPA 150.1
Conductivity	Electrometry (YSI Conductivity Meter)	EPA 120.1
Alkalinity (Total Carbonate, Bicarbonate)	Titration (pH 8.3, 4.5)	EPA 310.1
TIC	NDIR (Beckman 915A)	EPA 415.1
TOC	Oxidation—NDIR (Beckman 915A)	EPA 415.1
COD	Dichromate Reflux/Titration	EPA 410
BOD_5	5-Day Incubation/O_2 Change	SM 507
Phenol	Distillation/Colorimetry (4-AAP)	EPA 420.1
Chloride	Potentiometric Titration	SM 407 A.C
Fluoride	Ion Selective Electrode	SM 413 B
TDS	Gravimetry, dried at 180°C	EPA 160.1
TVDS	Gravimetry, ignited at 550°C	EPA 160.4
Cyanide, Total	Distillation/Colorimetry (PBA)	EPA 335.2
Cyanide, Free	Distillation/Colorimetry (PBA)	Ro
Thiocyanate	Colorimetry	SM 412K
Ammonia	Distillation/Titration	EPA 350.3
Sulfate	Turbidity	EPA 375.4
Sulfite	Titration	EPA 377.1
Sulfide	Zn Acetate Precipitation, Titration	EPA 376.1
Nitrate	Colorimetry	SM 418D
Nitrite	Colorimetry	SM 419
Trace Elements	ICPES, AAS	EPA* 200.7, EPA 200
Extractable Organics ($C_{8}+$)	Solvent extraction, GC, GC/MS	EPA* 624, 625

[a] EPA — U.S. EPA, Methods for Chemical Analysis of Water and Wastes, EPA 600/4-79-020, March 1979.
SM — APHA, AWWA, and WPCF, Standard Methods for the Examination of Water and Wastewater, 15th Edition, Washington, DC, American Public Health Association, 1980.
Ro — Roberts, R.F. and B. Jackson, "The Determination of Small Amounts of Cyanide in the Presence of Ferrocyanide by Distillation Under Reduced Pressure," Analyst, 96, 209-212, 1971.
EPA* — U.S. EPA, Proposed Rules, 44 Fed. Reg. 69468-69478, December 3, 1979.



All sample aliquots stored at 4°C except for trace element analyses.

Figure D-1. Sample preservation for water analyses.

TABLE D-2. SUMMARY OF SPECIAL SAMPLING OR HANDLING REQUIREMENTS

Determination	Container[a]	Minimum Sample Size (mL)	Preservation[b]	Proposed Maximum Holding Time[c]
Alkalinity	P, G	200	Refrigerate	14 days
BOD	P, G	1,000	Refrigerate	48 hr
Carbon, total inorganic (TIC)	P, G	100	Refrigerate	not given
Carbon, total organic (TOC)	G	100	Analyze immediately, or refrigerate and add H_2SO_4 to pH < 2	28 days
COD	P, G	100	Analyze as soon as possible; or add H_2SO_4 to pH < 2	28 days
Chloride	P, G	300	Refrigerate	28 days
Conductivity	P, G	500	Refrigerate	28 days
Cyanide, total[d]	P, G	500	Add NaOH to pH > 12, refrigerate in dark	14 days
Fluoride	P	300	None required	28 days
Metals, general	P(A), G(A)	—	For dissolved metals filter immediately, add HNO_3 to pH < 2	6 months
Nitrogen:				
Ammonia	P, G	500	Analyze as soon as possible or add H_2SO_4 to pH < 2, refrigerate	28 days
Nitrate	P, G	100	Add H_2SO_4 to pH < 2, refrigerate	48 hr
Nitrite	P, G	100	Analyze as soon as possible or refrigerate; or freeze at -20°C	48 hr
Organic compounds:				
Extractable	G	1,000	Refrigerate in specially cleaned amber glass bottles	7 days(until extraction) 30 days(after extraction)
pH	P, G	—	Analyze immediately	2 hr
TDS	P, G	—	Refrigerate	7-14 days
TVDS	P, G	—	Refrigerate	7-14 days
Sulfate	P, G	—	Refrigerate	28 days
Sulfide	P, G	100	Refrigerate; add 1 mL 2N zinc acetate/100 mL; pH > 12 with NaOH	28 days
Sulfite	P, G	100	Refrigerate; pH > 12 with NaOH	48 hr
Thiocyanate[d]	P, G	500	Add NaOH to pH > 12; refrigerate in dark	not given

[a] P = plastic (polyethylene or equivalent); G = glass; G(A) or P(A) = rinsed with 1 + 1 HNO_3.

[b] Refrigerate = storage at 4°C in the dark.

[c] Source: Environmental Protection Agency, Proposed Rules, Federal Register, 44: No. 244, December 19, 1979.

[d] Samples should be tested for presence of sulfides and oxidizing agents; these species must be removed prior to adjusting pH.

TABLD D-3. LABORATORY QUALITY CONTROL FOR RANDOMLY SELECTED DUPLICATE SAMPLES

SAMPLE IDENTIFICATION	TOTAL ALKALINITY	CONDUCTIVITY	AMMONIA	TOTAL CYANIDE	PHENOL	SULFIDE	SULFITE	THIOCYANATE
I25-1600	-	-	11800	-	-	-	-	-
	-	-	11300	-	-	-	-	-
I25-1800	-	-	-	-	-	75	-	-
	-	-	-	-	-	81	-	-
C25-1800	-	-	-	-	-	-	16	-
	-	-	-	-	-	-	17	-
I27-1650	-	-	-	-	-	54	68	-
	-	-	-	-	-	59	67	-
E27-1140	-	-	730	-	-	-	-	-
	-	-	680	-	-	-	-	-
E27-1240	-	-	650	-	-	-	-	-
	-	-	640	-	-	-	-	-
E27-1340	-	3920	-	-	-	-	-	-
	-	4360	-	-	-	-	-	-
E27-1530	37	-	700	-	-	-	-	-
	37	-	680	-	-	-	-	-
E27-1650	-	4900	800	-	-	45	19	-
	-	4900	830	-	-	47	19	-
E27-1730	-	5420	-	-	-	-	-	-
	-	5500	-	-	-	-	-	-
I01-1400	-	-	-	79	11	-	-	-
	-	-	-	81	11	-	-	-

TABLE D-3. (continued)

SAMPLE IDENTIFICATION	TOTAL ALKALINITY	CONDUCTIVITY	AMMONIA	TOTAL CYANIDE	PHENOL	SULFIDE	SULFITE	THIOCYANATE
E01-1400	-	-	690	-	26	-	-	-
	-	-	690	-	23	-	-	-
E01-1700	-	-	750	-	-	-	-	-
	-	-	760	-	-	-	-	-
E01-1800	-	-	-	33	15	-	-	-
	-	-	-	30	17	-	-	-
C01-1100	-	-	74000	-	-	-	-	-
	-	-	75400	-	-	-	-	-
C01-1200	-	-	71400	-	-	-	-	-
	-	-	74000	-	-	-	-	-
C01-1400	-	-	-	-	47	-	-	-
	-	-	-	-	40	-	-	-
C01-1530	-	-	-	-	36	-	-	-
	-	-	-	-	29	-	-	-
I01-1200	37800	-	11900	-	-	-	-	680
	37800	-	11050	-	-	-	-	680
I02-1600	-	-	10800	-	-	-	-	-
	-	-	12600	-	-	-	-	-
I02-1700	-	-	12300	-	-	-	-	-
	-	-	12600	-	-	-	-	-
E02-0900	-	-	390	-	-	-	-	-
	-	-	400	-	-	-	-	-

TABLE D-3. (continued)

SAMPLE IDENTIFICATION	TOTAL ALKALINITY	CONDUCTIVITY	AMMONIA	TOTAL CYANIDE	PHENOL	SULFIDE	SULFITE	THIOCYANATE
E02-1300	-	-	610	-	-	-	-	-
	-	-	610	-	-	-	-	-
E02-1600	-	-	-	-	-	-	-	630
	-	-	-	-	-	-	-	610
C02-1700	-	-	-	-	37	-	-	-
	-	-	-	-	33	-	-	-
I05-1130	-	4900	860	-	-	-	-	-
	-	4590	880	-	-	-	-	-
I05-1230	-	-	-	48	-	-	-	-
	-	-	-	42	-	-	-	-
I05-1630	-	-	-	50	-	-	-	-
	-	-	-	50	-	-	-	-
C05-1000	-	-	1660	-	-	-	-	-
	-	-	1590	-	-	-	-	-
C05-1130	-	-	1240	-	-	-	-	-
	-	-	1260	-	-	-	-	-
C05-1730	5533	-	-	-	-	-	-	-
	5530	-	-	-	-	-	-	-

duplicate/replicate analyses is presented in Table D-3 for the parameters alkalinity, ammonia, cyanide, sulfite, thiocyanate, and fluoride.

EPA quality control samples were analyzed for cyanide, fluoride, nitrate, TOC, and COD during the course of the program. The results of these tests are presented in Table D-4.

BULK WASTEWATER SAMPLE

The wastewater used in this study was obtained during a test run at the METC gasifier. Several drums of wastewater were collected during three steady-state operating periods on November 14, 15, and 18, 1983. During this time both low-sulfur bituminous and high-sulfur coal were gasified at a system pressure of 930 kPa (135 psig). In addition, the high-sulfur coal was gasified at a higher pressure, 1470 kPa (213 psig), during the sampling conducted on November 18. Circulating wastewater in the gas cooling section of the process was sampled at system pressure using a specially-designed dissolved gas sampling apparatus (DGSA). The DGSA enabled the wastewater to be flashed to ambient pressure at a controlled temperature. The flash temperature was controlled at 54°C (130°F) on November 14-15, and 59°C (138°F) on November 18. Flashed wastewater was collected in new steel drums with removable lids. After filling, the drums were sealed and shipped to Radian's Austin, Texas headquarters, where they were placed in refrigerated storage prior to use.

During the period of wastewater collection, grab samples of each stream were obtained at approximately three-hour intervals. These samples were returned to the Radian on-site mobile laboratory and were immediately analyzed for pH, conductivity, ammonia, cyanide, thiocyanate, sulfide, and sulfite. In addition, equal amounts of each of the individual grab samples were combined to form a single composite for each stream. These composites were preserved for additional analyses at Radian°s Water/Wastewater Research (WWRL) and Analytical Services Laboratories (RASL) in Austin, Texas. All analyses were

TABLE D-4. RESULTS OF THE ANALYSIS OF EPA QC SAMPLES FOR WATER QUALITY PARAMETERS[a]

Parameter	EPA True Value (mg/L)	Radian Analyzed Value (mg/L)	% Recovery
Cyanide #1	0.185	0.185	100
#2	0.578	0.642	90
Fluoride	1.12	1.24	110
Nitrate	1.32	1.2	91
TOC	92	100	109
COD	233	215	90

[a]Analyses were performed on separate samples specifically for the parameter indicated.

TABLE D-5. RESULTS OF WATER QUALITY ANALYSIS OF S-19 DURING RUN 103[a,b]

	Low Pressure Bituminous	
	11-14-83	11-15-83
pH (pH units)	8.59	8.54
Ion Balance	0.012	0.002
Conductivity (μmhos/cm)	50,000	100,000
HCO_3 as $CaCO_3$	36,800 ± 1,000	40,100 ± 3,000
CO_3 as $CaCO_3$	3,600 ± 800	5,000 ± 2,500
HS	520 ± 80	480 ± 15
SO_3	26 ± 6	56 ± 10
SO_4	260	400
CN^-	170 ± 10	170 ± 12
SCN^-	290 ± 30	760 ± 26
NH_4 as N	12,500 ± 50	13,500 ± 130
Cl^-	830	390
F	93	72
Formate as $HCOO^-$	15	12
Phenol	4,000	4,400
Acidity	0	0
TOC	7,500	5,500
TIC	6,900	7,900
Oil and grease	5,800	15,000
Settleable solids	11	8
TSS	42	16
TDS	3,240	2,960
TVS	2,660	2,700
BOD_5	3,100	3,000
COD	20,000	16,000

[a] All results as μg/mL (ppm) unless indicated otherwise.
[b] Source: W.A. Williams and B.J. Hayes, "Unique Wastewater Characterization of DOE/METC 42-inch Gasification Pilot Plant Effluents: Final Report," Radian Corporation for U.S. DOE/METC, (Contract No. DE-AC21-81MC16547), July 16, 1984.

completed within seven days of sample collection. The results of the on-site/ off-site analyses are given in Table D-5.

The wastewater drums were shipped to Austin and were stored upon arrival (four days after collection) at approximately 4°C in a cooler in Radian's warehouse. One drum of wastewater from each sampled stream was analyzed to determine sample stability during shipping. The results of the analyses are presented in Table D-6.

TABLE D-6. WATER QUALITY ANALYSIS OF STORED METC WASTEWATER

	Sample Collection Date		
	11-14-83[a]	11-15-83[a]	11-14-83[b]
pH (pH units)	--[c]	--	8.71
Conductivity (mhos/cm at 25°C)	--	--	38,600
Total Alkalinity as $CaCO_3$ (mg/L)	--	--	40,200
Ammonia as N (mg/L)	11,960	13,260	12,600
Phenol (mg/L)	4,360	4,580	4,160
Total Cyanide (mg/L)	--	--	56

[a]Analyses performed on 3-16-84.

[b]Analyses performed 5-15 through 5-20 1984.

[c] -- Means not analyzed.

APPENDIX E

PACKED-BED STRIPPING COLUMN DESIGN

The design of a wastewater stripper involves the determination of two important parameters. First, the tower diameter must be large enough to allow the flow of the wastewater and stripping steam while maintaining acceptable pressure drop and column hydraulic performance. Second, the depth of packing or the number of contacting stages (i.e., the tower height) must be sufficient to effect the required degree of species removal. The procedures followed in determining these two parameters for a packed-bed stripping column are discussed below.

E.1 TOWER DIAMETER

The tower diameter can be estimated based on generalized pressure drop correlations such as that developed by Sherwood (1), and later extended by Lobo (2) and Eckert (3). A recent refinement has been published by the Norton Co. (4). Their correlation is given in terms of dimensionless ordinate and abscissa functions, Y and X, with the column pressure drop per foot of packing, $\Delta P/z$, as a parameter. Y and X are defined as follows:

$$Y = 10.764\, G^2 F_\nu^{0.1} / [\rho_G(\rho_L - \rho_G)] \qquad \text{(E-1)}$$

$$X = L\sqrt{\rho_G}/G\sqrt{\rho_L} \qquad \text{(E-2)}$$

where L = superficial liquid mass velocity, kg/m^2 sec

G = superficial gas mass velocity, kg/m^2 sec

ρ_L = liquid density, kg/m^3

ρ_G = gas density, kg/m^3

F = packing characterization factor; value depends on the specific size and shape of packing chosen.

ν = liquid kinematic viscosity, centistokes

$\Delta P/z$ = pressure drop per unit packed bed height, mm water column/m

Tabulated values of packing factors for a variety of different sizes and shapes can be found in numerous literature references (e.g., References 4 and 6). The packing factors listed have been found to vary only slightly with changes in the superficial liquid flow rate (4), but they depend strongly on the method of installing the packing (6). The pressure-drop data of various investigators show wide discrepancies, sometimes as much as 60 percent for the same type of packing and flow rates, presumably owing to differences in apparent packing factors (5).

Note that the expression for X involves the ratio of the liquid and gas superficial mass velocities; since these are both defined as the mass flow rates divided by the tower cross sectional area, the ratio of mass flow rates, W_L/W_G can be used instead.

In order to use the correlation, the designer must specify the liquid and gas flow rates, liquid viscosity and density, gas density, the packing type and size to be used, and the appropriate pressure drop per meter of packing. Some general guidelines regarding packing size and pressure drop have been given in the literature (4,6):

- In general, packings smaller than 25 mm (1 inch) are intended for towers 0.30 m (1 foot) or smaller in diameter; packings of 25 to 38 mm (1 inch to 1 1/2 inch) are for towers between 0.30 to 0.90 m (1 to 3 feet) in diameter; and 50 or 75 mm (2 or 3 inch) packings are for towers 0.9 m (3 feet) or more in diameter. The nominal packing size should typically be between 1/8 to 1/15 the tower diameter.

- Gas absorbers and strippers are usually designed for low pressure drop operation (i.e., somewhere between 16 and 50 mm water per meter (0.20 and 0.60 inches of water per foot) of packing depth).

The value of Y corresponding to X and the chosen value of $\Delta P/Z$ is found using the correlation. The value of Y is used to solve for the only unknown remaining; the superficial gas velocity G. Since, as indicated previously, G is defined as the ratio of the gas mass flow rate, W_G, and the tower cross-sectional area, the tower diameter, d, may be found as:

$$d = \left[\frac{4}{\pi} \times \frac{W_G}{G} \right]^{1/2} \qquad \text{(E-3)}$$

The use of this correlation assumes that gas and liquid flow rates and physical properties are essentially constant over the tower height. If they are not, the tower may be designed based on the location where the largest flow rates are expected.

E.2 TOWER PACKING HEIGHT

A stripping tower must provide sufficient contact area between the aqueous and vapor phases to allow the desired mass transfer of contaminants to occur. The height of packing necessary to effect the desired removal is usually calculated as the product of two terms as in Equation E-4 below:

$$Z = (HTU) \cdot (NTU) \qquad \text{(E-4)}$$

where Z = packing height, m

HTU = height of a transfer unit, and

NTU = number of transfer units required.

The problem becomes one of calculating each of these two terms. The following derivation shows how this can be done in terms of measurable quantities.

For a given species being stripped from the liquid to the gas phase, the following mass balance equation may be written over a differential height of packing:

$$-L_M dx = K_L a\,(x_{ie} - x_i)\,\rho_M dz \qquad \text{(E-5)}$$

where L_M = superficial liquid molar velocity, kg moles/m^2 sec

x_i = mole fraction of species i in the liquid

x_{ie} = mole fraction of species i in equilibrium with gas

K_L = overall mass transfer coefficient, kg moles/(m^2)(sec)(kgmoles/m^3)

a = interfacial area between gas and liquid phases, m^2/m^3

ρ_M = liquid molar density, kg moles/m3

z = packed bed height, m

Integrating over the packed bed height and assuming that the liquid molar flow rate is constant (a fairly good approximation for the dilute solutions typically encountered in wastewater stripping operations), the following is obtained after rearrangement:

$$Z = \frac{L_M}{K_L a \rho_M} \int_{xi\ in}^{x_{i\ out}} \frac{dx}{(x_{ie} - x_i)} \qquad \text{(E-6)}$$

For dilute solutions and where the vapor-liquid equilibrium relationship for i is linear, the integral given in the equation above may be approximated as follows:

$$\int_{x_{i\ in}}^{x_{i\ out}} \frac{dx}{(x_{ie} - x_i)} = \frac{x_{i\ out} - x_{i\ in}}{(x_{ie} - x_i)_{L.m.}} \qquad \text{(E-7)}$$

$$\text{where } (x_{ie} - x_i)_{L.m.} = \frac{(x_{ie} - x_i)_{out} - (x_{ie} - x_i)_{in}}{\ln\left[\frac{(x_{ie} - x_i)out}{(x_{ie} - x_i)in}\right]} \qquad \text{(E-8)}$$

$x_{i,out}$ = mole fraction of i in the effluent

$x_{i,in}$ = mole fraction of i in the liquid feed

$x_{ie,out}$ = mole fraction of i in an aqueous solution in equilibrium with the gas at the bottom of the tower

$x_{ie,in}$ = mole fraction of i in an aqueous solution in equilibrium with the gas at the top of the tower

Note that if the gas entering the bottom of the stripper is pure steam, then $x_{ie,out}$ equals zero and only one equilibrium concentration must be calculated (i.e., $x_{ie,in}$). The other terms ($x_{i,out}$, $x_{i,in}$) represent measurable concentrations.

The integral in Equation E-6 defines what is known as the "number of transfer units" for the species in question, while the other terms define the "height of a transfer unit". Thus the packing height required for a given separation is the product of the transfer unit height and the required number of transfer units.

The above development is valid for either isothermal or non-isothermal operation. Heats of absorption can probably be assumed to be negligible for the concentrations encountered in most stripping operations. Heat losses, on the other hand, may be significant, especially for smaller diameter stripping columns. These losses may require that a differential heat balance equation be solved simultaneously with the differential mass balance (6).

The concentration of species i in an aqueous solution in equilibrium with the gas at the inlet and outlet of the stripper (x_{ie} in and x_{ie} out) are determined by the simultaneous solution of:

- species conservation equations,
- ionic balance equations, and
- thermodyanic relationships describing vapor-liquid and ionization equilibria.

Species conservation means that the total amount of a given species in all ionic states is a constant. For example, in a wastewater containing CO_2, NH_3, and H_2S, carbon dioxide may be present in several forms, including H_2CO_3, HCO_3^-, $CO_3^=$, and NH_2COO^-. Species conservation requires that the sum of the total mass of these species in the stripper effluent streams equal their mass in the feed water to the stripper. Similar relationships exist for the other species in solution.

Ionic balance requires that the total amount of negative charge contributed by the anionic species in water (e.g., $CO_3^=$, HCO_3^-, OH^-) be equal to the total amount of positive charge contributed by the cations (e.g., NH_4^+, H^+). Ionic balance may be solved implicitly with species conservation by treating charge as a conserved species.

Equilibrium expressions for chemical reactions such as the dissolution of a gas in water or the ionization of species in solution may be written in terms of an equilibrium constant based on the activities of the reactants and products:

$$K = \frac{(\Pi a_i \nu_i) \text{ products}}{(\Pi a_i \nu_i) \text{ reactants}} \qquad \text{(E-9)}$$

where K = equilibrium constant

a_i = activity of species i

ν_i = stoichiometric coefficient for species i

For an ideal gas, the activity may be expressed simply as the partial pressures of the species:

$$a_j = p_i \qquad \text{(E-10)}$$

The activity of a species in solution may be expressed as the product of an empirical correlation factor, the activity coefficient (γ), and the concentration of the species in solution, expressed in terms of any convenient set of units, such as molality, m (gmoles of solute/kg solvent):

$$a_j = \gamma_j m_j \qquad \text{(E-11)}$$

Since for water the molality is a constant, it may be included in the numerical value of the equilibrium constant. For example, for CO_2 dissolving in water, the reaction may be written:

$$CO_2(g) + H_2O(1) = H_2CO_3(1) \qquad \text{(E-12)}$$

The equilibrium expression for this reaction is:

$$K_{pCO2} = a_{H_2CO_3}/(p_{CO_2}\gamma_{H_2O}) \qquad \text{(E-13)}$$

The calculation of liquid compositions in equilibrium with a measured gas composition can be done using a computerized vapor-liquid equilibrium routine (such as Radian's Species Distribution Model (SDM)) which solves the set of simultaneous species conservation, ionic balance, and chemical equilibrium equations (7).

The interfacial area term, a, found in Equation E-5 depends on the specific packing being used, the gas density, and the liquid and gas mass flow rates in the column. Correlations have been developed for some packings relating these variables for stripping and absorption in aqueous systems (6).

Often the mass transfer coefficient times the interfacial area is reported as a single term, $K_L a$; this factor is known as the volumetric overall mass transfer coefficient.

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